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THE ENVIRONMENT AND HISTORY OF THE TOROWEAP AND KAIBAB FOR- MATIONS OF NORTHERN ARIZONA AND SOUTHERN UTAH

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PART I

I. INTRODUCTION

ACKNOWLEDGMENTS

The study of the rim rocks of Grand Canyon and their correlatives in the region was started in the summer of 1933 and has been continued to the present for the purpose of supplementing previous work on the underlying Coconino sandstone and of answering some of the many questions related to the general program of educational work in the Grand Canyon National Park. Thanks to the assistance of the Trustees of the Carnegie Institution of Washington and of its president, Dr. John C. Merriam, this program of research has been made possible through the placing of generous grants at the disposal of the writer.

Owing to the wide scope of this monograph and the many fields touched upon, the writer has sought and been given the assistance of numerous specialists and others during the progress of the work. For constructive criticism and helpful suggestions many thanks are due to Professors Ries and Nevin of Cornell University, Dr. Ian Campbell of the California Institute of Technology, Dr. N. E. A. Hinds of the University of California, and Dr. J. Volney Lewis and Mr. Edward Schenk of the National Park Service.

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For assistance in the field work at various times appreciative thanks are extended to the writer's wife, Barbara H. McKee, and to Messrs. Russell Wheeler, Russell Grater, and L. F. Brady. For laboratory assistance thanks are due especially to Mr. Craig Hinamon and for photographic help to Messrs. Hugh Waesche and Natt Dodge. Mr. C. E. Van Gundy was also very helpful in several phases of the work.

OBJECTIVE AND METHODS OF PROCEDURE

This paper on the environment and history of the Middle Permian marine formations of northern Arizona and southern Utah represents a study in palæogeography, using that term in the broad sense as defined by Dr. E. C. Case.¹ It deals with a particular time in geologic history—a critical period when conditions were extreme, with glaciation widespread in the southern hemisphere, great aridity prevailing in many places to the

¹ Geography is "the response of life to the conditions surrounding it." Palæogeography is the geography of past time. See Carnegie Inst. Wash. Pub. No. 283, p. 1, 1919.

north, apparent land connections between the Old and New Worlds, and mighty mountain uplifts in various parts of the earth. It deals also with a particular region—one where the records of this time are preserved better, perhaps, than in any other. The study, in brief, represents an attempt to reconstruct as accurately as the record will permit in the time available the ecological conditions of a particular time and place.

The Plateau Province, because of the nature of its terrain, affords exceptionally fine opportunities for carrying on investigations of the type here discussed. As G. K. Gilbert stated many years ago in referring to this region, "the simplicity of its structure, the thoroughness of its drainage which rarely permits detritus to accumulate in its valleys, its barrenness and the wonderful natural sections exposed in its cañons, conspire to render it indeed 'the paradise of the geologist.' There he can trace the slow lithologic mutations of strata continuously visible for hundreds of miles."² This condition is in direct contrast with that in most other regions, where data concerning the extent and lateral variation of widespread formations must be gleaned from scattered outcrops or isolated exposures and the nature of changes as well as the correlation between formations of various areas must be largely a matter of speculation.

In this palæogeographic study advantage has been taken of the unique natural conditions. A series of detailed sections of the strata involved was made from east to west in the walls of Grand Canyon, wherever trails or natural breaks made the rocks accessible. When lateral changes illustrated by beds of any two adjacent sections appeared to be too great to be explained with certainty, as in the eastern part of this area, one or more intermediate sections were examined in order to avoid the necessity of theorizing. Corresponding series of east-west sections were measured to the south in the region of the Mogollon Plateau, and to the north near the Utah-Arizona border. Also a general north-south series, extending northward as far as San Rafael Swell, Utah, added materially to an understanding of the problem. These latter exposures were not comparable with those in the Grand Canyon in continuity or completeness, nor were they for the most part as readily accessible; however, many of the facts and principles ascertained in the Grand Canyon were found applicable to the other areas.

Following the preliminary work of measuring sections, representative collections of fossils from the most critical horizons and areas were made, and careful observations and studies of special features such as cherts and gypsum deposits were undertaken in the field. This work was then supplemented by examination of the rock types in thin-sections, by chemical and mechanical analyses, and by comparison and analysis of the fossil collections. Only by consideration of all these various lines of evidence could justice be done to such a highly complex subject. Since an environment

² G. K. Gilbert, *Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871, 1872, and 1873*, U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 43, 1875.

involves "the sum of all the contacts which an organism or a group of organisms establishes with the forces and matter of its surroundings, either organic or inorganic,"³ every possible type of approach in this study was desirable.

HISTORICAL REVIEW

The earliest reference to the uppermost group of marine and related deposits of Middle Permian age in the Colorado Plateau is by Jules Marcou, who traversed the area from east to west in 1853-1854 as a member of Lieutenant Whipple's exploring expedition. In traveling from the Little Colorado River toward the base of the San Francisco Mountains, Marcou noted⁴ beneath what he termed the New Red Sandstone "a magnesium limestone, or thick dolomite, regularly stratified, in beds six inches to one foot in thickness" containing a bed of poorly preserved fossils among which he believed that he recognized fragments of *Belemnites*?, a *Nautilus*?, and a *Pteroceras*?. These beds and others farther west he considered to be equivalent to the European Permian formation known as the Magnesian Limestone. Other outcroppings of magnesian limestone in the same series but lower were noted by Marcou⁵ a few miles west of Bill Williams Mountain at Partridge and Cedar Creeks, but at this locality he found a brachiopod fauna which he considered similar to that of the Mountain Limestone or Lower Carboniferous of Europe.

In 1857 another eminent geologist, J. S. Newberry, examined the series of Permian sediments while crossing the Colorado Plateau from west to east with a party sent out by the War Department under Lieutenant Ives. Considering the great physical handicaps encountered and the unfavorable conditions for doing geological work, the data obtained and conclusions reached are truly remarkable. Newberry⁶ measured several sections, collected numerous fossils which he later described, and made rather careful analyses of the stratigraphy and of certain sedimentary problems.

The canyons of Partridge and Cedar Creeks referred to by Marcou were also examined by Newberry, who recognized in their profiles three divisions: two limestone cliffs separated by beds of gypsum. Unlike Marcou, however, he considered, on palæontological evidence, that both of the limestones were of Upper Carboniferous age, only locally separated by gypsum, and that they were not of Permian and Lower Carboniferous age respectively. As evidence that Marcou's claim of adding a new member (Permian) "to the series of secondary rocks in North America" was not valid, Newberry

³ E. C. Case, *The environment of vertebrate life in the late Paleozoic in North America: a paleogeographic study*, Carnegie Inst. Wash. Pub. No. 283, p. 40, 1919.

⁴ Jules Marcou, *Résumé and field notes*, U. S. Pacific Railroad Expl., vol. 3, pt. 4, Geological report, pp. 23-24, 153, 1856.

⁵ *Ibid.*, p. 69; also *idem*, *Geology of North America* (Zürich: Zürcher & Furrer; New York: Wiley & Halsted), p. 156, 1858.

⁶ J. S. Newberry, *Report upon the Colorado River of the West, explored in 1857-58 by Lieut. J. C. Ives* (Washington: Government Printing Office), pt. 3, Geological report, 1861.

pointed out⁷ that no proof of age was furnished by lithologic characters or by superposition. He stated that the chemical composition of the rock was insufficient basis for correlation with the Magnesian Limestone of Europe inasmuch as most of the limestones of far western North America are more or less dolomitic, and that, since the limestones possess the same lithologic characters as near-by limestones containing known Carboniferous fossils, a Carboniferous age seemed probable.

Between the time of Newberry's exploration and the close of the century, six other geological expeditions carried on studies in the Colorado Plateau area and contributed to our knowledge of the uppermost Paleozoic strata of the area. These strata were named in 1875 by G. K. Gilbert, who stated that "it was found convenient [on the Colorado Plateau] by Mr. Marvine and myself, to attach local names to the more important subdivisions. They are the Aubrey limestone, the Aubrey sandstones, and the Redwall limestone."⁸ The first of these divisions was comprised of the various deposits discussed in this paper.

The Aubrey strata were classed by Gilbert and Marvine⁹ as Permo-Carboniferous on the basis of certain fossils which they collected in the area east of Grand Canyon. These fossils, Marvine states, are considered by Meek "as being the equivalent of the Permo-Carboniferous fossils of Kansas," and Gilbert suggests that "the great lithologic change at this horizon marks the absolute close of the Carboniferous age."

In his study of the geology of the Uinta Mountains published in 1876, Major J. W. Powell¹⁰ adopted the term Aubrey, previously introduced by Gilbert, and he referred to an upper and a lower Aubrey group. These names, however, he also applied to "a series of sandstones with intercalated cherty limestones" near the junction of the Green and the Grand Rivers, and likewise to beds in the Uinta Mountains, neither of which correlations is now considered valid. In the Uinta Mountains, furthermore, Powell¹¹ divided his Upper Aubrey into two members: the Bellerophon limestone above and the Yampai sandstone below. The Bellerophon limestone he considered to be represented at the junction of the Grand and the Green, and the name has subsequently been applied to the uppermost part of the true Aubrey limestone farther south. Powell regarded it "as not improbable that the time of the Permian period may be represented in the Plateau Province by the Upper Aubrey group, although the distinguishing types are wanting there."¹²

⁷ *Ibid.*, pp. 70-73.

⁸ G. K. Gilbert, *Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871, 1872, and 1873*, U. S. Geol. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 177, 1875.

⁹ G. K. Gilbert, *op. cit.*, p. 177; A. R. Marvine, *Report on the geology of the route from St. George, Utah, to Gila River, Arizona, examined in 1871*, U. S. Geol. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 213, 1875.

¹⁰ J. W. Powell, *Report on the geology of the eastern portion of the Uinta Mountains*, U. S. Geol. and Geol. Survey Terr., 2d div., p. 54, 1876.

¹¹ *Ibid.*, p. 149.

¹² *Ibid.*, p. 80.

In 1880 Dr. C. D. Walcott, in writing on the geology of Kanab Valley, placed¹³ the uppermost Paleozoic limestones, which he described as chocolate-colored, in the Permian because of the fauna of pelecypods and gastropods which they contained. These beds he maintained were above the Carboniferous limestones of the Upper Aubrey but equivalent in part to the Permo-Carboniferous of Marvine and the Permian Magnesian Limestone of Marcou.

Since the beginning of the present century some seventy papers have been published in which the Aubrey limestone of Gilbert and Marvine has been described or discussed in varying detail, for the most part in reference to particular areas. In the Grand Canyon district, L. F. Noble has been the principal contributor. In the area to the south and southeast of Grand Canyon, Robinson and Darton have given information, and to the northeast, in the isolated Utah exposures, work has been done by Gregory and Moore, Gilluly, and others. In western Arizona and Utah rather extensive studies of the formation have been made by Reeside and Bassler and by Longwell, while still farther west in Nevada, Hewett and others have added to our general knowledge of the problem. No attempt is made to review the conclusions and contributions of each of these geologists; however, a complete bibliography of their papers on this subject may be found at the end of part I of this monograph.

The name of the formation under consideration was officially changed to Kaibab limestone by Darton¹⁴ in 1910, and this name has been retained. Darton explains that "the upper limestone of the Carboniferous in northern Arizona has heretofore been known as the 'Aubrey' limestone, but as Aubrey has now been adopted by the United States Geological Survey for the group of which this limestone forms a part, a distinct name is required for it. Accordingly Kaibab has been selected, from the Kaibab Plateau, on the north side of the canyon, which is capped by the formation in typical development over a very large area."

By far the most important step of recent years in developing an understanding of the history of the so-called Kaibab limestone was the recognition by Noble¹⁵ of "members" of contrasting character in the Grand Canyon sections. This introduced into the literature the significant fact that actually a large proportion of the beds grouped under the name Kaibab are not limestones but sandstones, red beds, gypsum deposits, and other distinctive types. The plan advanced by Noble of subdividing into members was later expanded by Reeside and Bassler,¹⁶ who, working in the Colorado Plateau region farther west where the sections were thicker

¹³ C. D. Walcott, *The Permian and other Paleozoic groups of the Kanab Valley, Arizona*, Amer. Jour. Sci., 3d ser., vol. 20, p. 221, 1880.

¹⁴ N. H. Darton, *A reconnaissance of parts of northwestern New Mexico and northern Arizona*, U. S. Geol. Surv. Bull. 435, p. 28, 1910.

¹⁵ L. F. Noble, *The Shinumo Quadrangle, Grand Canyon district, Arizona*, U. S. Geol. Surv. Bull. 549, p. 70, 1914.

¹⁶ J. B. Reeside Jr. and Harvey Bassler, *Stratigraphic sections in southwestern Utah and northwestern Arizona*, U. S. Geol. Surv. Prof. Paper 129, p. 58, 1922.

and more nearly complete, emphasized a fivefold topographic and lithologic division. These units have since proved to be fairly constant features from eastern Grand Canyon westward as far as outcrops of Middle Permian rocks occur, but to the northeast, east, and southeast of this area there are marked lateral transitions in essentially all the groups.

Curiously enough, one of the most recent developments in the history of Kaibab investigations was the selection of a type section. In 1928 L. F. Noble wrote, "Although the Kaibab Plateau is the type locality for the Kaibab limestone, no detailed section of the formation has been made anywhere in the Plateau. Consequently no type section of the formation is on record."¹⁷ He therefore proposed as the type a section in Kaibab Gulch, "because it is the only section in the type area that is known to be complete."

GENERAL DESCRIPTION OF THE DEPOSITS

Marine and closely related deposits of Middle Permian age are clearly and extensively exposed over plateau surfaces and canyon and mesa walls throughout large areas in northern Arizona and to a less extent in southern Utah and Nevada. These deposits help substantiate the generalization made by Dutton that "the strata of the Plateau country are remarkable for their homogeneity or persistence of lithologic characters when considered with reference to their horizontal extensions. But when considered in the vertical sense they are almost as remarkable for the lithologic contrasts to be found among them."¹⁸ Marked contrasts are present even among the various "members" of the so-called Kaibab limestone, although the buff and gray limestone units are by far the most apparent because of their massive character, which produces prominent and widespread topographic expression.

At the type locality at Kaibab Gulch, Noble's subdivision B—the uppermost massive member that forms the surface of much of the plateau—is described as "composed chiefly of gray, crystalline, fossiliferous, cherty limestone but includes some beds of calcareous sandstone."¹⁹ This same cliff-forming limestone is similar in general appearance far to the west and southwest of the type locality, though there it is more crystalline and more fossiliferous. Even beyond the margins of the plateau in Utah and Nevada it forms conspicuous topographic features, standing as long, sharp ridges with nearly even tops in the highly faulted ranges of that area. Eastward and southeastward from the type section this limestone becomes distinctly more sandy and less cherty and the nature of its fauna changes completely, but it still is resistant and forms conspicuous cliffs.

¹⁷ L. F. Noble, *A section of the Kaibab limestone in Kaibab Gulch, Utah*, U. S. Geol. Surv. Prof. Paper 150, p. 41, 1928.

¹⁸ C. E. Dutton, *Mt. Taylor and the Zuni Plateau*, U. S. Geol. Surv. Sixth Ann. Rept., p. 131, 1885.

¹⁹ L. F. Noble, *A section of the Kaibab limestone in Kaibab Gulch, Utah*, U. S. Geol. Surv. Prof. Paper 150, p. 51, 1928.

In many places over the surface of the Colorado Plateau the massive limestone of subdivision B is overlain by a thin covering of variable beds that have collectively been referred to as the Harrisburg gypsiferous member, the Bellerophon limestone, and the Super Aubrey beds. In northwestern Arizona and the adjoining part of Utah, where these deposits have their maximum known thickness and where Reeside and Bassler made the first detailed studies of them, they are described as "highly variable in composition and thickness, consisting of shale, gypsum and limestone."²⁰ Southeastward from this area the gypsum and then the red beds disappear, but the highly magnesian limestones, which are thin-bedded and fine-grained and weather with a peculiar pitted surface, form a thin mantle above the massive beds over practically the entire area of deposition except where eroded from the plateau surface.

Inasmuch as the lower three subdivisions of the type section are, for the most part, seen only in canyon walls, it suffices for this general description to point out that the first and third of these consist of red beds and irregularly bedded sandstones, with interbedded gypsum deposits farther west, while the middle member is a massive limestone. Eastward near the upper end of Grand Canyon the limestone disappears and the other beds change in character to white, gnarly-bedded sandstones. The details of these lithologic units will be described in chapter II, "Sequence of Sediments and Unconformities."

DISTRIBUTION AND THICKNESS

The Middle Permian strata discussed in this paper lie in three states and have a known areal extent of many thousands of square miles. In the southern part of the area, outcroppings of at least one of these strata are found as far east as the Mogollon Rim near the town of Heber, Arizona, while the same stratum is represented westward in the Mule Spring Range in Nevada. The distance between these localities is over 300 miles. Farther north in Utah outcroppings indicate a minimum east-west extent of 94 miles, or from the vicinity of the Waterpocket Fold to the Mineral Mountains.

From north to south, distances between extreme exposures of the Middle Permian strata with which we are concerned in this paper are comparable with those from east to west. Along the eastern margin, about 300 miles separate outcroppings of San Rafael Swell, Utah, from those of the Mogollon Rim below Heber, Arizona, and in the west a distance of at least 160 miles stretches between Mineral Mountains, Utah, and the south end of the Aubrey Cliffs in Arizona. The extent and principal outcroppings of these strata may be readily visualized by reference to the map, figure 1.

A realization of the probable magnitude of the original marine basins represented by the limestone deposits or of the continental areas of deposi-

²⁰ J. B. Reeside Jr. and Harvey Bassler, *Stratigraphic sections in southwestern Utah and northwestern Arizona*, U. S. Geol. Surv. Prof. Paper 129, p. 58, 1922.

tion indicated by the intermediate layers of sediments can be obtained from present outcroppings. The western and southern limits of the strata are formed by the complete removal of untold quantities of corresponding beds, which must originally have extended much farther in each of these directions. Today on the west and south the beds end abruptly in cliffs and mountain ranges beyond which no traces of them have been found, but their great thickness and their nature in these areas indicate that they were formed far from the margins of depositional basins.

On the eastern and southeastern fronts of the present region of outcrops, the strata under discussion give fair evidence of their former extent. In some places the beds can be observed actually to thin and terminate; in others they pass from sight beneath thick layers of more recent age, but their nature indicates marginal areas.

Since, under the name of Aubrey limestone and, later, of Kaibab limestone, various types and kinds of deposits of Middle Permian age have long been grouped, a majority of the numerous measurements that have been made of these strata have involved the entire series without reference to the different members. For this reason they are of little value in a palæogeographic study of the type described in this report. On the other hand, measurements indicating the trends in thickening and thinning of the various units have since been made and will be given in discussing these units. In this introduction a few of the composite measurements are given to show the vertical extent of the deposits in addition to the lateral extent already indicated:

- Southeast:* Snowflake, Arizona, 6 feet *
- Heber, Arizona, 200 feet *
- Meteor Crater, Arizona, 150 feet *
- Flagstaff, Arizona, 200-300 feet *
- Northeast:* Marble Canyon, Arizona, 500 feet
- Circle Cliffs, Utah, 150 feet *
- Fruita, Utah, 290 feet *
- San Rafael, Utah, 85 feet *
- Central:* Eastern Grand Canyon, Arizona, 500 feet
- Bright Angel Trail, Arizona, 600 feet
- Point Sublime, Arizona, 600 feet
- Kanab Canyon, Arizona, 800 feet
- West:* Toroweap Valley, Arizona, 775 feet
- Near Hurricane, Utah, 930 feet
- Near St. George, Utah, 1050 feet
- Spring Mountain, Nevada, 700 feet

* Probably Kaibab only; underlying sandstone may not be Coconino but Toroweap equivalent.





FIG. 1. Index map showing location of measured sections; also section lines that are represented in figures 2 to 7 and 12 to 22

PUBLISHED SECTIONS OF THE TOROWEAP AND KAIBAB FORMATIONS

Number on base map	Locality	Reference to publication *
1	4 mi. SE. of Holbrook, Ariz.	McKee, this paper, p. 177
2	11 mi. SE. of Holbrook, Ariz.	McKee, this paper, p. 177
3	7 mi. N. of Snowflake, Ariz.	McKee, this paper, p. 177
4	Snowflake, Ariz.	Darton (10), p. 99
5	4 mi. NE. of Pinedale, Ariz.	McKee, this paper, pp. 177-178
6	Black Canyon, Sec. 27, T. 14, R. 17	Darton (10), p. 96
7	Heber, Ariz.	Darton (10), p. 96; McKee, this paper, p. 178
8	Chevelon Creek, 13 mi. SE. of Winslow	Darton (10), p. 96
9	Chevelon Creek, Sec. 6, T. 16, R. 17	Darton (10), p. 96
10	Chevelon Creek, Sec. 6, T. 15, R. 16	Darton (10), p. 96
11	Chevelon Creek, 25 mi. S. of Winslow	Darton (10), p. 97; McKee, this paper, pp. 178-179
12	Clear Creek, 3 mi. SE. of Winslow	Darton (10), p. 96; McKee, this paper, p. 179
13	Clear Creek, 4 mi. SSE. of Winslow	Darton (10), p. 96
14	Clear Creek, Sec. 27, T. 17, R. 15	Darton (10), p. 96
15	Clear Creek, Sec. 21, T. 17, R. 15	Darton (10), p. 96
16	10 mi. SW. of Winslow	McKee, this paper, p. 179
17	Clear Creek, Township 14	Darton (10), p. 96
	Mack's Crossing, East Clear Creek	McKee, this paper, pp. 179-181
18	East Clear Creek and Miller Canyon	McKee, this paper, pp. 181-182
19	Mogollon Rim, 8 mi. W. of Coconino- Sitgreaves Boundary, Ariz.	McKee, this paper, p. 182
20	Mogollon Rim, above Washington Park	McKee, this paper, p. 182
21	Long Valley	McKee, this paper, p. 182
22	Clover Creek, 0.5 mi. W. of main road	McKee, this paper, pp. 182-183
23	Pivot Canyon, 0.5 mi. W. of main road	McKee, this paper, p. 183
24	Schnebley Hill	McKee, this paper, pp. 183-184
25	Oak Creek Canyon, west side	McKee, this paper, pp. 184-185
26	Padre Canyon at Highway 66	McKee, this paper, p. 185
27	Walnut Canyon	Shimer and Shimer (78); H. W. Shimer (77), pp. 473-474; McKee, this paper, pp. 185-186
28	Sycamore Canyon, 15 mi. SE. of Bill Williams Mtn.	Gilbert (17), pp. 162-166
	Sycamore Canyon, west side	McKee, this paper, pp. 186-187
29	Partridge and Cedar Creeks	Marcou (50), pp. 154-156; Newberry (59), pp. 68-69
30	Aubrey Cliffs, NW. of Seligman, Ariz.	McKee, this paper, pp. 187-189
31	Tolchico on Little Colorado	McKee, this paper, p. 189
32	Grand Falls, Little Colorado	Gregory (25), pp. 25-26; McKee, this paper, p. 189
33	Citadel Sink	McKee, this paper, p. 190
34	Rimey Jim's, N. of Flagstaff	McKee, this paper, p. 53 (no measure- ments)
35	30 mi. S. of Grand Canyon, Grandview- Flagstaff road	McKee, this paper, p. 190
36	10 mi. W. of Cameron, Ariz.	McKee, this paper, pp. 190-191
37	Little Colorado, base of Waterloo Hill	McKee, this paper, pp. 191-192
38	Lee Canyon	McKee, this paper, p. 192-193

* Numbers in parentheses refer to bibliography, page 218.

Number on base map	Locality	Reference to publication *
39.....	Straight Canyon	McKee, this paper, pp. 193-194
40.....	Little Colorado N. of Cedar Mtn.	McKee, this paper, pp. 194-195
41.....	Desert View, Grand Canyon	McKee, this paper, pp. 195-196
42.....	Congress (Red) Canyon, Grand Canyon	Frech (16)
	Red Canyon (Hance Trail), Grand Canyon	H. W. Shimer (77), p. 475; McKee, this paper, pp. 196-198
43.....	Kaibab (Yaki) Trail, Grand Canyon	McKee, this paper, pp. 198-200
44.....	Bright Angel Trail, Grand Canyon	McKee, this paper, pp. 200-201
45.....	Hermit Trail, Grand Canyon	McKee, this paper, pp. 201-203
46.....	Bass Trail, Grand Canyon	Noble (63), p. 72
	Fossil Mtn., Grand Canyon	McKee, this paper, pp. 203-204
47.....	Hilltop, Havasu Canyon	McKee, this paper, pp. 204-206
48.....	Canyon of Cascade (Havas) River	Newberry (59), p. 62
49.....	Middle of Toroweap Valley	H. W. Shimer (77), p. 479
	Toroweap Valley, east side	McKee, this paper, pp. 206-208
50.....	Toroweap Valley, west side	Reeside and Bassler (73), pp. 69-70
51.....	2 mi. N. of Point Imperial, Grand Canyon	McKee, this paper, pp. 208-209
52.....	Lees Ferry, Marble Canyon	Bryan (47), p. 16
	Marble Gorge opposite Badger Canyon	Moore (27), pp. 43-44; McKee, this paper, pp. 209-211
53.....	Jacob's Pool, northern Arizona	Gilbert (17), pp. 161-166
54.....	House Rock Valley, south end, west side	H. W. Shimer (77), pp. 476-479
55.....	Jumpup Canyon near Kanab Creek	Noble (64), pp. 54-55
56.....	Hack's Canyon, Ariz.	Reeside and Bassler (73), p. 69
57?.....	Kanab Creek, Lower Canyon	Gilbert (17), p. 161
	Kanab Canyon	Walcott (83), p. 222
58.....	Kaibab Gulch	Noble (64), pp. 43-46
59.....	Circle Cliffs, Utah, S. of Ohio Oil Co. well	Moore (27), p. 42
	Circle Cliffs, SSW. of Ohio Oil Co. well	McKee, this paper, pp. 211-212
60.....	Circle Cliffs, Ohio Oil Co. well no. 1	Moore (27), p. 157
61.....	Circle Cliffs, SW. of The Peaks	McKee, this paper, pp. 212-213
62.....	Circle Cliffs, W. of The Peaks	Moore (47), pp. 20-21; (27), p. 41
63.....	Circle Cliffs, near Mule Twist Canyon	Dake (7), p. 63
64.....	Circle Cliffs, NE. of Wagonbox Mesa	Moore (27), p. 41
65.....	Circle Cliffs, N. of The Peaks	Moore (27), p. 41
66.....	3 mi. SE. of Torrey; 10 mi. NW. of Fruita	Dake (7), p. 67
67.....	Dirty Devil Canyon near Fruita	Dake (7), p. 66
68.....	San Rafael Swell, 9.5 mi. S. of Wickiup	McKee, this paper, p. 213
69.....	San Rafael Swell, Black Box Canyon	Gilluly (19), pp. 80-81
70.....	San Rafael Swell, 0.5 mi. in Black Box	McKee, this paper, pp. 213-214
71.....	San Rafael Swell, east end, Black Box	McKee, this paper, p. 214
72.....	4 mi. E. of Minersville, Utah	Lee (38), p. 10; (37), p. 363; McKee, this paper, pp. 214-215
73.....	5 mi. S. of Kanarraville	Lee (37), p. 362
74.....	LaVerkin Canyon, bet. Toquerville and Colob	Huntington and Goldthwait (35), p. 203
75.....	Mouth of Virgin Canyon, 0.5 mi. S. of LaVerkin	Reeside and Bassler (73), p. 72

* Numbers in parentheses refer to bibliography, page 218.

Number on base map	Locality	Reference to publication *
76.....	Hurricane Fault, 6 mi. S. of Hurricane	Reeside and Bassler (73), pp. 71-72
77.....	Antelope Wash, head of Rock Canyon	Reeside and Bassler (73), pp. 70-71
78.....	Rock Canyon, north side, 15 mi. S. of Hurricane	Reeside and Bassler (73), p. 71
79.....	Hurricane Fault, Black Rock Canyon	Reeside and Bassler (73), p. 70
80.....	Harrisburg Dome, 8 mi. NE. of St. George	Reeside and Bassler (73), pp. 73-74
81.....	Washington Dome, 6 mi. E. of St. George	Reeside and Bassler (73), p. 74
82.....	Bloomington Dome, 5 mi. S. of St. George	Reeside and Bassler (73), pp. 74-75
83.....	Narrows of Virgin below Bloomington	Reeside and Bassler (73), pp. 75-76
84.....	St. George-Wolf Hole Rd., 7 mi. N. of Wolf Hole	Reeside and Bassler (73), p. 75
85.....	Black Rock Spring, 25 mi. S. of St. George	Reeside and Bassler (73), p. 75
86.....	Beaver Dam Mtns., 20 mi. NW. of St. George	Reeside and Bassler (73), pp. 76-77
87.....	Grand Wash Cliff, E. of Bronze-L mine	Longwell (44), p. 41
88.....	Upper Terrace, near mouth Grand Canyon	Gilbert (17), pp. 162-166
89.....	Pakoon Ridge, 1.5 mi. N. of Black Canyon	Longwell (44), p. 42
90.....	2 mi. S. of Mud Well	Longwell (44), p. 42
91.....	Grand Wash Canyon, east side Wash	Longwell (44), pp. 42-43
92.....	Muddy Mtns.	McKee, this paper, p. 22 (no measure- ments)
93.....	Meadow Valley Canyon below Hack- berry	Spurr (79), pp. 134, 135
94.....	Cottonwood Escarpment, Spring Mtns.	Glock (21), pp. 332, 333
95?.....	Spring Mtn. range, Cottonwood Creek	Gilbert (17), pp. 162-166
95.....	NE. of Cottonwood Spring	Glock (42), p. 332
96.....	Bird Spring Mtns., E. of Cottonwood Pass	Hewett (32), p. 31
97.....	NW. of Mule Spring Mtn.	Hewett (32), p. 31
98.....	SE. of Mule Spring Mtn.	Hewett (32), p. 31
99.....	Mesa, SE. of Diamond Creek	Newberry (59), p. 60
100.....	Spring Mtns. at Goodsprings, Nev.	McKee, this paper, p. 215

* Numbers in parentheses refer to bibliography, page 218.

II. SEQUENCE OF SEDIMENTS AND UNCONFORMITIES

PROPOSED CLASSIFICATION AND NOMENCLATURE OF THE SEDIMENTARY UNITS

The use of the name Aubrey limestone for the group of Middle Permian marine beds and certain associated continental deposits of the Colorado Plateau, and the later change of this name to Kaibab limestone, have been in line with steadily increasing knowledge of these strata. In the light of present studies, involving detailed investigation of the beds over the entire region, however, these names, which have for so many years served the purpose well, now appear to be inadequate.

The Kaibab limestone of Darton, the writer believes, represents not one but two distinct formations. The basis for separation is found, first, in the presence of a widespread unconformity involving local warping and general erosion; second, in the distinctive faunas in the limestone phases of each; and, lastly, in an abrupt change in lithology.

The name Kaibab should be retained for the upper of the two formations, in the writer's opinion, since in the type locality and elsewhere it consists in large measure of a massive cherty limestone which forms conspicuous features of the landscape. Consequently, there is little doubt that this is the portion of the group that most, if not all, geologists working in the region have in mind when reference to the name is made. Indeed, it is probable that few have realized that several other distinctive types of sediments, actually constituting a high percentage of all the sediments in the group, have been included under this name.

The use of the term "limestone" in the name Kaibab limestone, although more appropriate for the formation as redefined in this report, is still misleading. It fails to convey the important fact that complete sections of the formation, as in the extreme eastern Grand Canyon, are composed of sandstone essentially free of limestone, and that elsewhere, as in the uppermost strata in many places, continental red beds and gypsum deposits of no small thickness are found. For these reasons it is suggested that the name *Kaibab formation* be used instead of Kaibab limestone.

The heretofore unrecognized formation which underlies the Kaibab as defined in this paper, and which in most areas immediately overlies the Coconino sandstone, consists in the type locality of two red-bed series separated by a massive limestone unit. It includes the subdivisions C, D, and E of the Kaibab limestone as used by earlier writers. Since this formation is well exposed in the east wall of Toroweap Valley, Arizona, the writer proposes for it the name *Toroweap formation*. This name is entirely in keeping with the policy used in applying other formational names in the area, for, as in the case of Kaibab, Coconino, and others, it comes from a major geographical feature in which is represented an excellent type section of the formation.

The writer's investigation of the Toroweap and Kaibab formations shows the subdivisions of the group as applied by Reeside and Bassler¹ and by Noble,² i. e. the five members, to be the most satisfactory for general use over a major part of the area. Westward from eastern Grand Canyon, Aubrey Cliffs, and Kaibab Gulch these members can be recognized in every section. Farther east, however, difficulties are encountered in applying the system; consequently, certain modifications are necessary in order adequately to describe the character of, and to call attention to changes in, the formations. Detailed studies, furthermore, have brought to attention marked lateral changes within the members making it desirable to recognize divisions within them.

The three lower members—those comprising the Toroweap formation—disappear completely or change character eastward from Grand Canyon, so that they lose their identity in that direction. In the eastern area of Toroweap deposition the entire formation is composed of light-colored, cross-laminated sandstone; therefore, in that area subdivision into members is not possible. This change in lithologic character of the formation from west to east is brought about by interfingering of units. For this reason it is desirable to divide the formation laterally into a western phase and an eastern phase, and to designate the intermediate area, where sedimentary types are mixed, as the transition phase. Only the western phase is divided into members. For these, the designations α , β , and γ are proposed, representing respectively the upper red member or time of receding sea, the limestone member or time of extended sea, and the lower red member or time of advancing sea.

The upper two members used in the classification of Reeside and Bassler—now considered divisions of the Kaibab formation—maintain more or less distinctive character throughout the area of their exposure although gradual but definite changes in lithology and fauna occur in each. Southeastward from Grand Canyon a third member is found at the base. As in the case of the Toroweap formation, these members of the Kaibab are designated as α , β , and γ , characterizing the time of retreating sea (upper), the time of extended sea (middle), and the time of advancing sea (lower).

Detailed study of many sections of the Toroweap and Kaibab formations has made apparent the fact that, during the deposition of each member, the conditions of sedimentation were so varied even within short lateral distances as to produce markedly different rocks usually characterized by distinctive groups of fossils. A condition somewhat comparable, in the Borden rocks of Indiana, has been observed and studied by Stockdale, who states concerning the variations that “upon their understanding hinges the elucidation of the stratigraphy.”³ He has, as a result, introduced a classi-

¹ J. B. Reeside Jr. and Harvey Bassler, *Stratigraphic sections in southwestern Utah and northwestern Arizona*, U. S. Geol. Surv. Prof. Paper 129, p. 58, 1922.

² L. F. Noble, *A section of the Kaibab limestone in Kaibab Gulch, Utah*, U. S. Geol. Surv. Prof. Paper 150, p. 43, 1928.

³ Paris B. Stockdale, *The Borden (Knobstone) rocks of southern Indiana*, Indiana Dept. Conservation, Pub. No. 98, p. 75, 1931.

fication embodying the use of facies as units of comparable age but distinctive character. Kindle,⁴ following a discourse on modern ecological conditions, has emphasized the same point and stated that the recognition of facies, both lithologic and faunal, is necessary to a classification that will convey a true picture of the complex conditions of an area such, for instance, as one involving a combination of continental, shore, near shore, lagunal, and other types.

Although the classification used by Stockdale has served admirably to convey an idea of the complex conditions found in the Borden rocks, modification has been necessary to permit its application to the Kaibab-Toroweap sequence. Stockdale's main divisions in each formation are lateral ones termed facies. He states that the formations "cannot be subdivided into members that are recognizable throughout the *entire* Borden outcrop area; however, mappable layers are found which are of sufficient distribution and persistence in character to designate them as members of a particular facies."

In the Kaibab-Toroweap formations the major units recognized are those in vertical series which have been termed "members." An exception to this exists in the Toroweap formation, where two major east-west types, designated as phases, are also present. The term "facies" has been applied by the writer to units of distinctive lithologic and faunal character which are recognized laterally within the members. A classification of the phases, members, and facies that are described in this paper, with the characteristics and distribution of each, is summarized in tables 2 and 4, pages 18 and 43. Detailed descriptions of these units are given in following parts of this chapter under the headings "Facies of the Toroweap Formation" and "Facies of the Kaibab Formation."

In order that there may be no confusion as to the meaning of certain other terms used throughout this paper, these are briefly defined.⁵ A *tongue* is a specially developed part of a varied formation which wedges out laterally in one direction and in the other thickens and becomes part of a larger body of like sediments. *Bed* and *layer* designate the smallest units recognized in classification; thus they constitute the vertical subdivisions of a member. *Zone* is a subordinate unit containing the rocks deposited during the time of existence of a particular fauna.

CONTACT BETWEEN THE COCONINO SANDSTONE AND THE TOROWEAP FORMATION

In an earlier paper⁶ the writer pointed out that the cross-bedded upper levels of the Coconino sandstone were beveled to a perfectly flat surface

⁴ E. M. Kindle, *The rôle of facies in stratigraphic paleontology*, Proc. Geol. Soc. Amer., 1933.

⁵ Definitions are according to *Classification and nomenclature of rock units*, Bull. Amer. Geol. Soc., vol. 44, pp. 423-459, 1933.

⁶ Edwin D. McKee, *The Coconino sandstone—its history and origin*, Carnegie Inst. Wash. Pub. No. 440, VII, p. 88, 1934.

and that this was overlain by a thin layer of red sandstone "near Seligman, throughout the Grand Canyon, and north of it," at all places where he had examined the formations in detail. Observations which the writer has made subsequently—in Parashant Canyon and Toroweap Valley, at Havasu Canyon, in Grand Canyon along the Hance Trail, below Point Imperial, and under Desert View, in Sycamore Canyon, and elsewhere—have shown that the same relationship exists at all of these widely separated places (plate 4). The contact is, therefore, even more remarkable for its widespread, consistent nature than was at first suspected.

Considerable difference of opinion has existed concerning the significance of the remarkably sharp contact between the Coconino sandstone and the overlying beds of the Toroweap formation as found in Grand Canyon and elsewhere. Although Noble⁷ and Frech⁸ are content simply to describe the contact as seen in Grand Canyon, both stress the lack of transition. Schuchert, on the other hand, points out that a "transition zone of interbedded limestone and sandstone [passing downward] into the Coconino sandstone [shows] clearly that these two formations belong to one unbroken cycle of deposition."⁹ Hager states that "the Kaibab limestone overlies the Coconino sandstone conformably."¹⁰ Longwell, referring to the contact as found in the Muddy Mountains of northwestern Arizona, is non-committal, stating that "the strong cross-bedding of the Coconino ends sharply, giving an impression either of unconformity or of changed conditions of sedimentation."¹¹ Of these two possibilities the writer strongly inclines toward the latter since there appears to be no vestige of relief on the Coconino surface and no conglomerate or other trace of an erosion preceding the deposition of Toroweap sediments. The term "unconformity," used by the writer in an earlier paper,¹² he now considers inappropriate. Extensive truncation of sloping Coconino laminæ to a perfectly flat surface can be accounted for only by a beveling of the sediments while still unconsolidated, and the waters that did this probably at the same time spread out the red mud and sand now forming the flat-lying beds on top. Thus it is probable that no appreciable hiatus is represented between the Coconino and Toroweap formations.

In strong contrast with the flat, apparently level top of the Coconino as found in the various localities just referred to is the channeled surface de-

⁷ L. F. Noble, *A section of the Paleozoic formations of the Grand Canyon at the Bass Trail*, U. S. Geol. Surv. Prof. Paper 131, pp. 69–70, 1922.

⁸ F. Frech, *Section in Congress Canyon opposite Point Sublime*, Compt. rend. 5th Sess., Cong. Géol. Internat., pp. 478–479, 1891.

⁹ Charles Schuchert, *On the Carboniferous of the Grand Canyon of Arizona*, Amer. Jour. Sci., 4th ser., vol. 45, p. 348, 1918.

¹⁰ Dorsey Hager, *Oil possibilities of the Holbrook area in northeast Arizona* (privately published), p. 15, 1921.

¹¹ C. R. Longwell, *Geology of the Muddy Mountains, Nevada, with a section through the Virgin Range to the Grand Wash Cliffs, Arizona*, U. S. Geol. Surv. Bull. 798, p. 39, 1928.

¹² Edwin D. McKee, *The Coconino sandstone—its history and origin*, Carnegie Inst. Wash. Pub. No. 440, VII, p. 88, 1934.

TABLE 1. LOCALITIES SHOWING COCONINO-TOROWEAP CONTACT EXAMINED BY THE WRITER

Place	Nature of Coconino top	Character of overlying sediments
Toroweap Valley.....	Steeply sloping beds truncated to perfectly flat surface	Sandstone, yellowish, fine-grained, calcareous, flat-bedded, sugary, 8.5 ft.
Hilltop, Havasu Canyon.	Same (extensively exposed)	Sandstone, red, hard, medium-sized quartz grains scattered through silt, 19.5 ft.
Fossil Mtn., Grand Canyon.....	Same	Sandstone, yellow, crumbly, calcareous, 1 ft., overlain by thin-bedded limestone
Hermit Trail, Grand Canyon.....	Same	Sandstone, red, medium-sized quartz grains scattered through silt, 7 ft.
Bright Angel Trail, Grand Canyon.....	Same	Sandstone, red and yellow, fairly resistant, medium-sized quartz grains in silt, thin-bedded above, 30 ft.
Kaibab Trail, Grand Canyon.....	Same	Sandstone, red, fairly resistant, medium-sized quartz grains scattered through silt, 8 ft.
Hance Trail, Grand Canyon.....	Same	Sandstone, red and yellow, both flat and gnarly beds, calcareous, medium-sized quartz grains in fine silt at base, 28 ft.
Desert View, Grand Canyon.....	Same	Sandstone, red and yellow, flat-bedded at contact, slightly cross-bedded above, calcareous, lenses of medium-sized quartz grains scattered throughout, 26.5 ft.
Point Imperial, Grand Canyon.....	Same	Mudrock, red, massive, calcareous, flat-bedded, 13.5 ft.
Lee Canyon, Little Colorado.....	Same	Sandstone, red and yellow, fine-grained, flat-bedded, calcareous, 20 ft. Highly cross-bedded above
Base of Waterloo Hill, Little Colorado.....	Fairly flat but appears undulating in places	Sandstone, red, yellow, and white, irregularly bedded, 20 ft. Highly cross-bedded above
10 mi. W. of Cameron, Little Colorado.....	Undeterminable	Sandstone, white, calcareous, gnarly-bedded, massive, 35 ft.
Aubrey Cliffs, near Seligman.....	Steeply sloping beds truncated to perfectly flat surface	Sandstone, red, fine-grained, calcareous, crumbly, soft, silty, 11 ft.
Sycamore Canyon.....	Same	Sandstone, yellow, flat-bedded, fine-grained, near top becomes gnarly and brecciated, 20 ft.
Badger Canyon, near Lees Ferry.....	Same	Sandstone, red, medium-sized quartz grains in fine matrix. Cross-bedded sandstone above, 17 ft.

scribed by the writer from a locality 15 miles south of Flagstaff. Here a sandy limestone was found filling small irregularities due to erosion. No doubt similar evidence found in Walnut Canyon, near by, was the basis for Shimer's statement that "these beds, the Coconino sandstone, disconformably underlie the Kaibab limestone."¹³ In more recent field examinations made by the writer evidences of a surface of slight relief at the top of the Coconino, with an overlying limestone filling small channels, were noted at Clover Creek and Pivot Canyon and at Mack's Crossing on East Clear Creek—all on the Mogollon Plateau south of Flagstaff.

The apparent inconsistency in the evidence furnished by the two types of contact found at the top of the Coconino is easily explained, since in all the areas where traces of erosion have been discerned, the Toroweap formation is found to be missing (or is represented by the uppermost Coconino-like sediments). Thus, in these places the unconformity occurs not between the Toroweap and Coconino formations, but, instead, between the Kaibab and the Coconino (or Toroweap). In San Rafael Swell and other places in eastern Utah where evidences of unconformity have been noted between the cross-bedded sandstones and the limestone deposits a similar relationship exists, i. e. Kaibab resting on Coconino (?) or on the equivalent of the Toroweap; thus these areas are not to be considered in a discussion of the Toroweap-Coconino contact.

FACIES OF THE TOROWEAP FORMATION

The Toroweap formation, as defined in this paper, includes those beds of sandstone, limestone, and gypsum that occur unconformably beneath the Kaibab formation (name used in restricted sense) and conformably above the Coconino sandstone in the Colorado Plateau and in certain adjacent mountain ranges to the northwest. Because of a complete lithological change occurring within the distance of a few miles laterally between distinctive western and eastern types, these are referred to as phases¹⁴ of the formation. The western phase is by far the larger in geographical extent and is the portion that is best known to geologists and that is represented in the type locality.

Since the Toroweap formation is particularly well exposed along the eastern wall of Toroweap Valley in Grand Canyon National Monument, Arizona, this has been selected as the type locality of the formation and a type section has been measured about 8 miles north of the Colorado River. This section is given on page 206.

In the type section of the Toroweap formation three distinct members are readily apparent. These are designated, from top to bottom, as the α , β , and γ members. The upper and lower ones consist largely of soft, friable

¹³ H. W. Shimer, *Permo-Triassic of northwestern Arizona*, Bull. Geol. Soc. Amer., vol. 30, p. 475, 1919.

¹⁴ Following the usage of the term by J. Barrell in *The Upper Devonian delta of the Appalachian geosyncline*, Amer. Jour. Sci., 4th ser., vol. 36, no. 215, p. 465, 1913.

TABLE 2. CLASSIFICATION OF UNITS IN TOROWEAP FORMATION

Status	Environment—locality	Character	Other names—fauna
WESTERN PHASE			
α member (upper red) . . .	Time of receding seas	Red beds, gypsum, chemical limestones	Subdivision B of Noble, 1922; subdivision C of Noble, 1927
Facies 1	Western area, i. e. from Hilltop westward	Red beds, thin-bedded limestones, gypsum deposits	No fauna except in one pelecypod limestone
Facies 2	Eastern area, i. e. from Fossil Mtn. to Hance Trail	Red beds	No fauna except in one pelecypod limestone
β member (limestone) . . .	Time of extended seas	Massive limestones	Subdivision C of Noble, 1922; subdivision D of Noble, 1927
Facies 1	Western area, i. e. Toroweap and westward	Massive, crystalline and dense, marine limestones	Fauna of molluscoid types (see plate 8)
Facies 2	Eastern area, i. e. Hilltop east to Desert View	Massive, impure, brackish-water limestones	Fauna of mollusks (see plate 8)
γ member (lower red) . . .	Time of advancing seas	Red beds, other sandstones and shales, gypsum in west	Subdivision E of Noble, 1927
Facies 1	Throughout area	Red beds and other sandstones. Gypsum reported in west, new facies?	No fauna
TRANSITION PHASE			
Intertongued type	Transition area, i. e. Hance Trail, Desert View, Sycamore Canyon	White cross-bedded sandstones fingering into red beds	No fauna
EASTERN PHASE			
Sandstone type	Eastern area, i. e. Little Colorado, Oak Creek Canyon	White cross-bedded and gnarly-bedded sandstones	No fauna

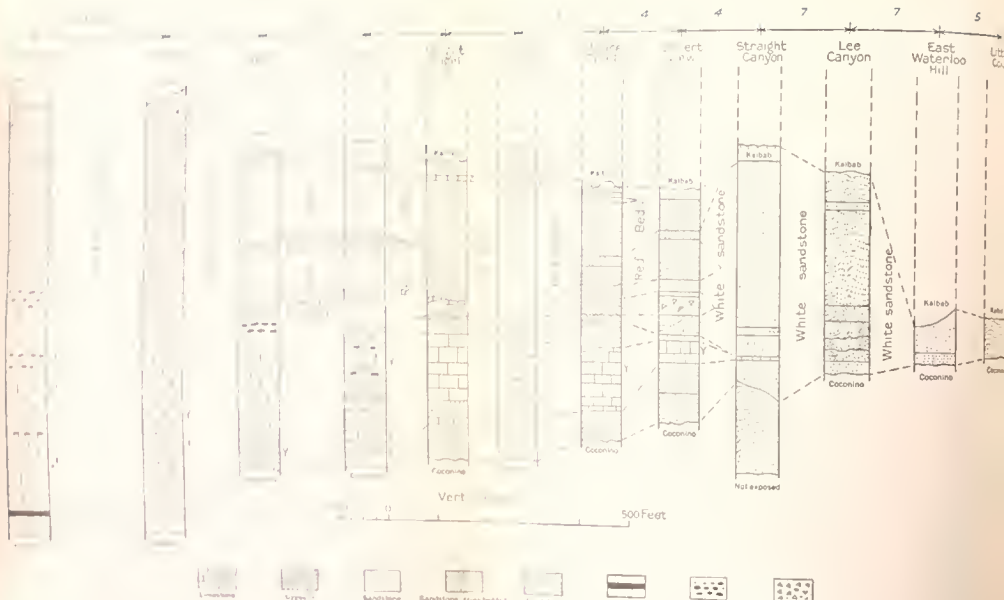


Fig. 1. West-east sections of Tropic formation.

- X Normal faunal zone (*P. subrectus* to *act.* fauna)
 N¹ Deep zone (*P. subrectus* to *act.* and *crinoids*)
 N² Like N¹ plus *C. tenuis* and *C. tips* etc.
 A¹ *Prod.* zone
 Y Brackish water zone (*P. subrectus* to *act.* fauna)
 Z *Schizodus* zone

sediments, mostly red beds, which everywhere weather rapidly to form slopes, while the β member is a resistant limestone which characteristically stands up as a prominent cliff between. These members are easily recog-

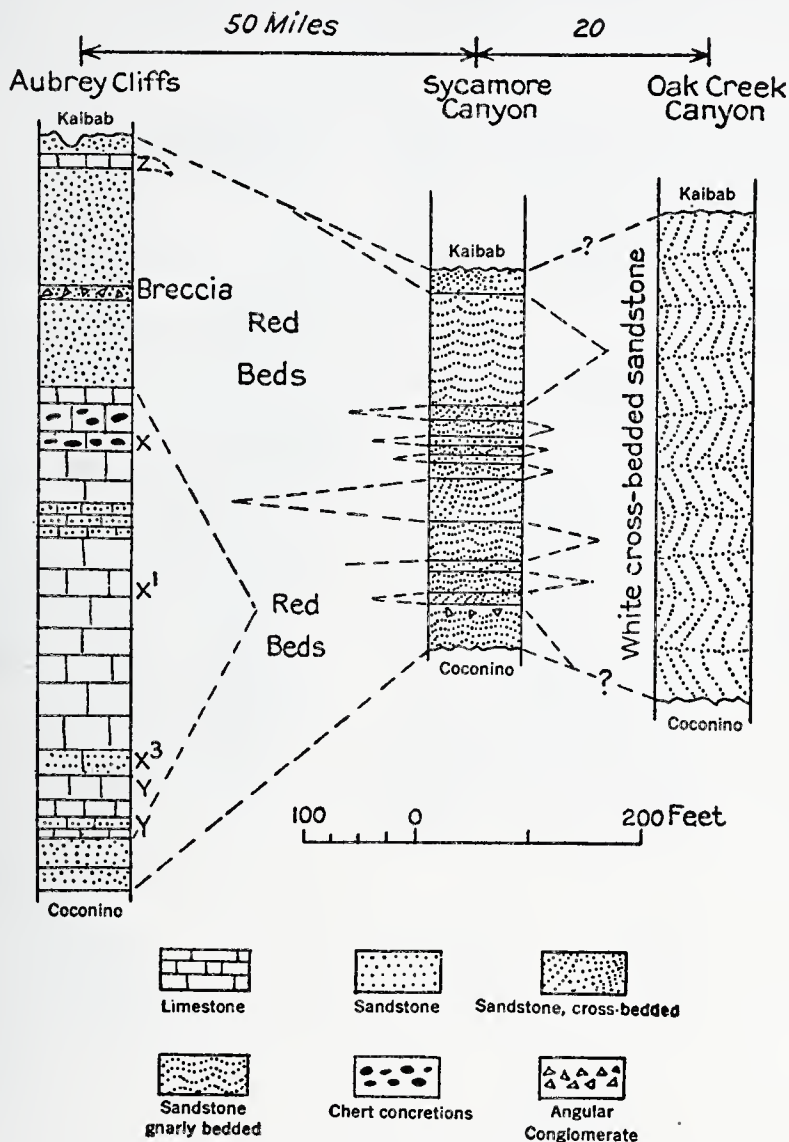


FIG. 3. West-east sections of Toroweap formation

- X = Normal marine or "*Productus ivesi*" fauna
 X¹ = *Archæocidaris*, *Productus ivesi*, and crinoids
 X³ = *Productus ivesi* only
 Y = Brackish-water or "*Bellerophon*" fauna
 Z = *Schizodus* only

nizable throughout a major part of the area of deposition and have been referred to in the literature as the C, D, and E members of the Kaibab limestone. Only in the extreme eastern part of the formation do these members change character so that they can no longer be recognized.

γ Member

The γ member of the Toroweap formation is composed largely of fine-grained sandstone of red and yellow color, flat or irregularly bedded except in the extreme east where it is cross-bedded on a small scale. It grades up-

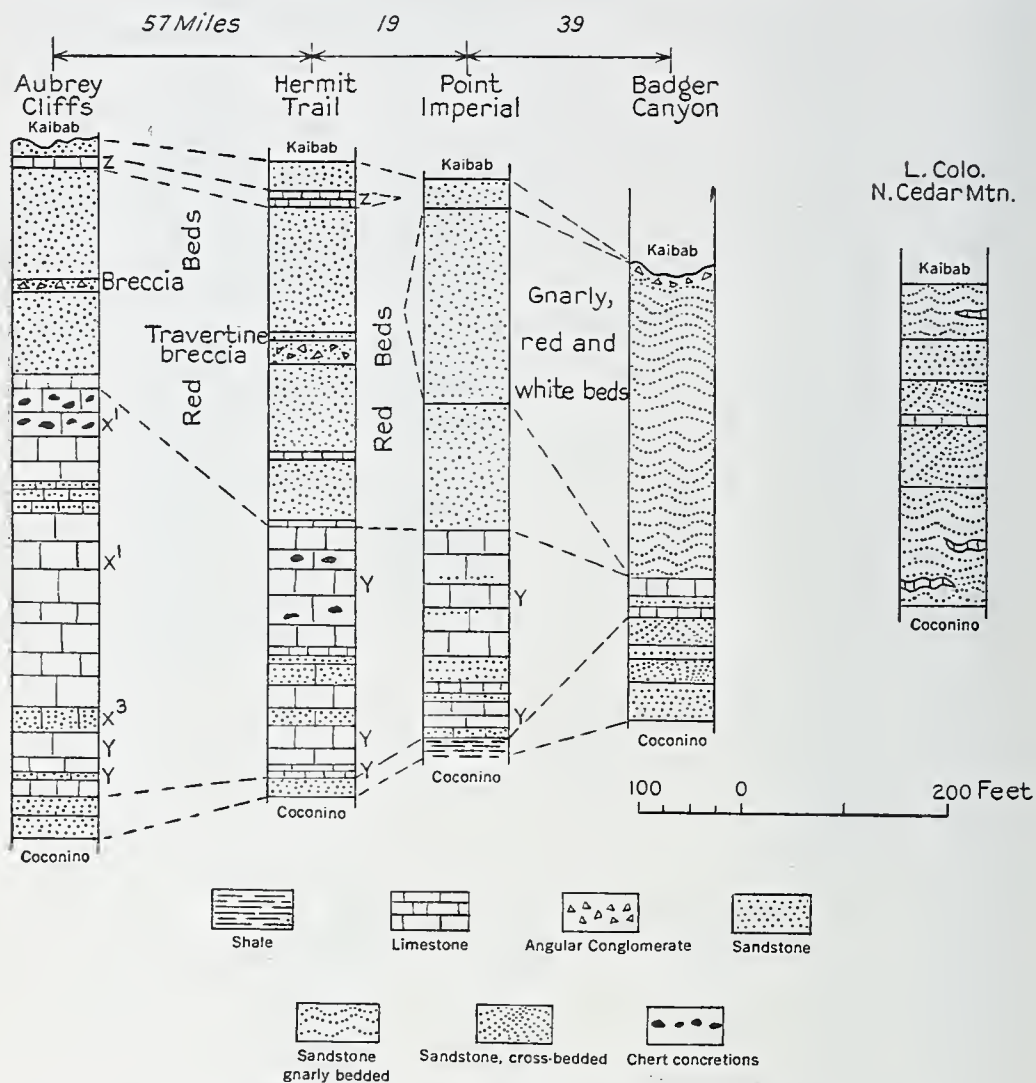


FIG. 4. Southwest-northeast sections of Toroweap formation

X = Normal marine or "*Productus ivesi*" fauna

X¹ = *Archæocidaris*, *Productus ivesi*, and crinoids

X³ = *Productus ivesi* only

Y = Brackish-water or "*Bellerophon*" fauna

Z = *Schizodus* only

ward as alternating beds into limestone of the β member. Its maximum observed thickness is about 50 feet and in most places is much less. In a general way the member thins from east to west, probably owing to the fact that the sea encroached over the area from the west causing lime deposition to replace sand deposition earlier in that direction.

Throughout the Grand Canyon and in most other areas where examined, the basal layer of the γ member, Toroweap formation, is a red sandstone or siltstone composed of Coconino-like quartz grains scattered through a finer-grained matrix. As already indicated in the discussion of the Coconino-

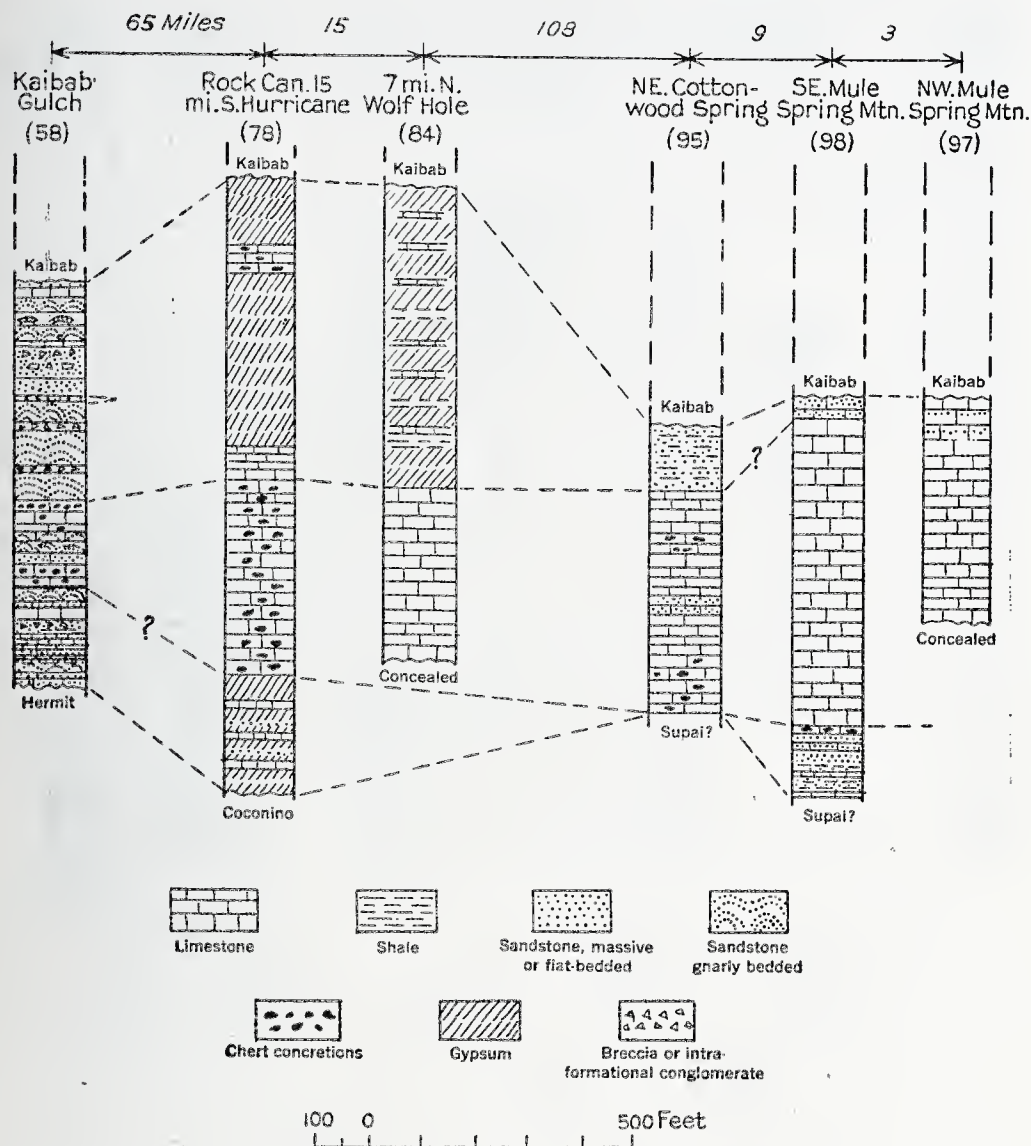


FIG. 5. East-west sections of Toroweap formation

Compiled from published sections by Noble, Reeside and Bassler, Longwell, Hewitt. Position of details within major rock units necessarily not accurate. Fossil zones not known. (Section numbers refer to base map and to list of published sections, page 9.)

Toroweap contact (page 15), it is thought that this feature, together with the remarkably flat upper surface of the cross-bedded Coconino sandstone, can be satisfactorily accounted for only by the beveling of an unconsolidated sand surface by an advancing sea. From this it is to be inferred that the red beds of the γ member of the Toroweap formation were deposited, at

least at the start, under subaqueous conditions. The upper irregularly bedded sandstones of this member may or may not represent similar conditions of deposition.

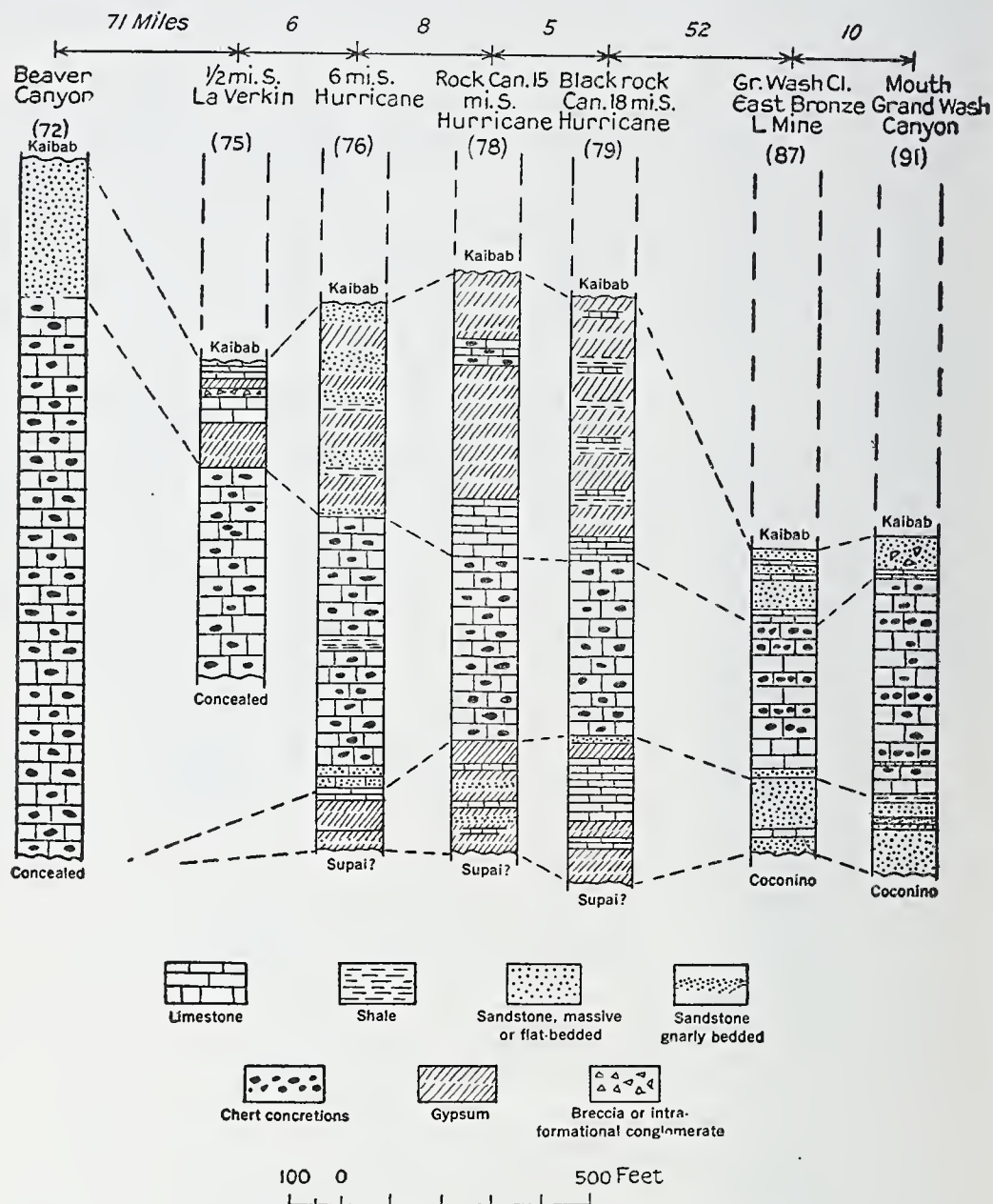


FIG. 6. North-south sections of Toroweap formation

Compiled from published sections by Lee, Reeside and Bassler, Longwell. Position of details within major rock units necessarily not accurate. Fossil zones not known. (Section numbers refer to base map and to list of published sections, page 9.)

In Grand Wash Canyon on Mead Lake, the red beds of the γ member were found to contain a very conspicuous layer of breccia only a few feet above the top of the Coconino sandstone. The angular fragments that make up this breccia obviously were derived from a near-by surface, and

because of the local character of the deposit, it is interpreted as an intra-formational conglomerate. This feature is discussed in detail in chapter III.

β Member

The β member of the Toroweap formation is a massive limestone which lies between the red sandstones of the γ and α members throughout the area which they cover. From a thickness of approximately 220 feet in the type section in Toroweap Valley, and somewhat more farther west, this limestone gradually becomes thinner toward the east and southeast and it is entirely missing in sections along the Little Colorado Canyon and in Sycamore Canyon. Below Desert View Point in Grand Canyon it is about 20 feet thick.

The limestone that constitutes the β member is divisible laterally into two parts or facies, characterized by differences in lithologic character and in fauna, but grading from one into the other. Facies 1 is represented in all outcrops that occur from the extreme western part of the formation east to Toroweap Valley and southeast almost to Seligman, Arizona. It is a marine limestone, coarsely crystalline for the most part, cherty in some horizons and containing a fauna of brachiopods and echinoids. Facies 2 is represented by the eastern portion of the limestone member and apparently was formed nearer the shore, probably under brackish-water conditions. It is fine-grained but, like the marine limestone of facies 1, is relatively free from clastics over much of the area; its fauna is almost exclusively molluscan, both pelecypods and gastropods being everywhere abundant but poorly preserved (plate 8).

The β member of the Toroweap formation is the true *Productus ivesi* limestone. The type of *Productus ivesi* Newberry came from near Diamond Creek, undoubtedly from this formation since the *Productus* limestone of the Kaibab formation has been removed by erosion from this area. As pointed out by Stoyanow¹⁵ and indicated in part II of this paper, "Systematic Description of Brachiopods," this productid is similar to yet consistently different from the larger form found in the overlying Kaibab formation, with which it has frequently been confused. *Productus ivesi*, furthermore, is the only animal, with the exception of a crinoid, known to occur in both facies of the β member of the Toroweap formation, and it is the only brachiopod that has been found in the "brackish water" portion.

A significant and interesting feature of the β member is found in its relationship to the members above and below. In nearly every locality where it was examined, a transition stage is represented by an intermediate thin-bedded, uniform-textured limestone. This limestone weathers into smooth, angular blocks of small size; each bed usually has a thickness of 1 to 2 inches; and the rock is highly magnesian but free from both clastics

¹⁵ A. A. Stoyanow, *Correlation of Arizona Paleozoic formations*, Bull. Geol. Soc. Amer., vol. 47, p. 528, 1936.

and fossils. It is believed by the writer that this limestone is a chemical precipitate that developed under arid conditions in the early stages of the advancing and retreating seas. In the western exposures, especially, these peculiar limestone beds recur at several horizons between red beds above the β member, thus forming a gradational contact between members.



FIG. 7. Map showing distribution of phases of Toroweap formation and of facies comprising β member of western phase

a Member

The upper or α member of the Toroweap formation is dominantly a red-bed series. In sections near its eastern limits, however, tongues of white,

cross-bedded sandstone extending out from the eastern phase of the formation occur among the red beds, while from Hilltop (Havasut Canyon) westward, gypsum and thin-bedded, highly magnesian limestones, thought to be chemical precipitates, make up a large portion of the member. Because of these lateral changes two lithologic facies are distinguished within the member, facies 2 being the eastern, without evaporation deposits; facies 1, the western, containing interbedded layers of gypsum and thin-bedded limestones.

Inasmuch as fossils are unknown from the α member, except at one horizon, its facies cannot be compared from this standpoint. Moreover, it seems reasonable to assume that the faunal differences were slight. Environmental conditions probably would have been more unfavorable to life in the area of playa deposition than in the surrounding areas; however, aridity and desiccation in both types of country would have assured a sparse plant and animal population. A discussion of the origin of the red beds, gypsum deposits, and limestones in the Toroweap formation is given in chapter III.

In many places throughout both facies of the Toroweap α member are found "breccias" or intraformational conglomerates. Since these are very local in character, they evidently do not represent any widespread or regional erosion cycles but probably are to be explained as purely local features of erosion formed during a period of general deposition. Associated with them in some places are travertines thought to have been formed in much the same manner as many such deposits are being formed today in arid areas of Nevada and adjoining regions. These intraformational conglomerates and travertines are discussed in detail in chapter III.

Another feature of considerable interest found in both facies of the Toroweap α member is a fossil-bearing limestone which occurs over a remarkably wide area without appreciable variation. Everywhere it has a thickness of only 3 or 4 feet. The fossils in it are of only one species, a representative of the pelecypod genus *Schizodus*, but are so abundant that in every locality examined the rock surfaces are speckled with their remains (plate 6b). This abundantly fossiliferous limestone is found on the Shivwits Plateau, in the Aubrey Cliffs, at Hilltop, Fossil Mountain, and along the Hermit, Bright Angel, and Kaibab Trails in Grand Canyon, always near the top of the red-bed series. At Hilltop it occurs almost immediately below bedded gypsum deposits. It is an excellent marker bed throughout this area, as it forms a definite contrast with the barren limestones of the member.

Eastern Phase

Below Desert View Point in Grand Canyon and in the walls of Sycamore Canyon to the south may be seen transition stages between the western phase of the Toroweap formation, just described, and the eastern phase, which is lithologically totally different. At the Grand Canyon locality a

very thin layer of β member limestone separates the red beds of γ and α members in the normal manner; however, at several horizons among the red beds are found layers of white cross-laminated sandstone, parts of tongues extending westward from the eastern phase, which occurs unmixed a few miles farther east. At Sycamore Canyon the transition phase is even more fully developed. The Toroweap formation consists from bottom to top of alternate layers of red beds and beds of white cross-bedded sandstone. This succession of the two types is repeated seven times.

Eastward from the transition phase of the Toroweap formation the change in lithologic character becomes complete. In this direction from Sycamore Canyon, unfortunately, no good exposures of the formation are accessible until Oak Creek Canyon is reached, about 20 miles away. Here, red beds are absent and the white, cross-bedded sandstones form a continuous cliff which is difficult to distinguish from the Coconino sandstone below. Probably the boundary between these formations occurs at the level where a persistent ledge or terrace separates the great cliff of undoubted Coconino and the smaller cliff that is considered the equivalent of the Toroweap but possesses in part characteristics of the Coconino.

Justification for the assumption that the upper sandstone cliff in Oak Creek Canyon is to be correlated with the Toroweap formation is found in a critical examination of its cross-lamination. Although locally consisting of the truncated wedges that are typical of normal Coconino sandstone, much of it consists of layers which are flat on top and bottom but composed of uniformly dipping laminae. Such beds are present, but less extensively developed, in Walnut Canyon farther east, suggesting that the Toroweap gradually changes character and, losing its identity where Coconino conditions prevailed, becomes indistinguishable from the true Coconino sandstone.

In the region east of Desert View Point in Grand Canyon where sections are conveniently exposed fairly close together, conditions are found that verify the validity of those postulated for the area farther south. In Straight and Lee Canyons and along the Little Colorado Gorge north of Cedar Mesa the upper limit of the Coconino is clearly defined and the considerable thickness of white sandstones between this and the Kaibab formation clearly demonstrates the nature of the transition into the eastern phase of the Toroweap formation.

In the western portion of Straight Canyon some red beds are present, but below Cedar Mesa in the same canyon they are lacking, and in both the Little Colorado and Lee Canyons—north and southeast respectively—they are also absent. In all these places white sandstone makes up the entire formation. In places it consists of uniformly sloping laminae within thick beds having flat upper and lower limits. Elsewhere it forms massive beds which locally are twisted and wavy (a type for which the writer proposes the term gnarly bedding, see chapter III, page 105) and within each of which is developed cross-bedding of the "scour and fill" type on a small scale. In a few places only have normal flat-bedded sandstones been noted.

TABLE 3. COMPARATIVE THICKNESSES OF SECTIONS, TOROWEAP FORMATION

	Toro- weap Valley	Hilltop	Fossil Moun- tain	Hermit Trail	Bright Angel	Kaibab Trail	Hance Trail	Desert View	Straight Canyon	Lee Canyon	East, Waterloo Hill	Little Colorado	Little Colorado North Cedar Moun- tain
α	190.0	204.5	142.0	165.0	173.0	175.0	146.5	138.0	183.5	.....	.....	.....	.....
β	218.5	183.5	123.0	113.0	86.0	63.0	52.0	18.5	3.0	.....	.....	.....	.....
γ	17.0	19.5	25.0	7.0	30.0	42.0	29.0	53.0	26.0	.....	.....	.....	.....
Total	425.5	407.5	290.0	285.0	289.0	285.0	227.5	209.5	212.5	185.0	48.5	35.0	147.0

TABLE 3--Continued

	Aubrey Cliffs	Hermit Trail	Point Imperial	Badger Canyon				Aubrey Cliffs	Sycamore Canyon	Oak Creek Canyon
α	106.5	165.0	161.0	147.0				106.5	.....	.....
β	190.5	113.0	96.5	13.5				190.5	.....	.....
γ	20.0	7.0	13.5	54.5				20.0	.....	.....
Total...	317.0	285.0	271.0	215.0				317.0	157.5	247.5

Along the Little Colorado Gorge only seven miles east of the Lee Canyon locality, the entire eastern phase of the Toroweap formation is represented by a maximum of not more than 50 feet of cross-bedded and gnarly-bedded sandstones. In explanation of this remarkable decrease in thickness (135 feet) in so short a distance, pre-Kaibab erosion might be suggested; however, the evidence that this erosion period was of slight duration on a surface of general low relief would make this appear unlikely. Abrupt thinning of beds of the eastern phase types on a marginal area seems to be the most likely explanation.

The section of the Toroweap formation near Badger Canyon, southwest of Lees Ferry, exhibits most of the characteristics found in those sections of the eastern phase near and along the Little Colorado. The same types of cross-bedded and flat-bedded sandstones are found in the lower portion, while the upper two-thirds is composed of gnarly-bedded sandstones. Thirteen and a half feet of limestone occurring 54 feet above the base is probably to be explained as part of a tongue of β member extending out from the western phase of the formation. It is clear that here none of the formation has been lost by change in character into the Coconino type of bedding as in areas farther south, for the readily recognizable red sandstone member that occurs at the formation base over most of the region is present, clearly indicating the lower limit and showing that the total thickness is but slightly less than in sections to the west.

UNCONFORMITY BETWEEN THE TOROWEAP AND KAIBAB FORMATIONS

In the extensive literature on the Permian strata of the Colorado Plateau the only suggestion that an unconformity occurs between the Toroweap and Kaibab formations is given by Noble.¹⁶ He describes a breccia at the top of his subdivision B at Fossil Mountain, and although he refrains from calling it a type of basal conglomerate, no doubt because of a lack of other evidence to substantiate such a theory, nevertheless he intimates that such might be a possible explanation. He describes the breccia as follows: "Composed chiefly of angular fragments of evenly-bedded, buff, fine-grained sandstone embedded in a matrix of fine lemon-buff sand; contains a few fragments of siliceous limestone. The fragments range in size from less than an inch to over four feet. The contact of the breccia with the underlying sandstone is wavy and irregular, exhibiting in places inequalities of several feet."

That other geologists have failed to note evidence of this unconformity is not altogether surprising in view of the generally unfavorable conditions for demonstrating its presence. Throughout much of the region where it is exposed, the Kaibab formation from its base to a considerable height above is massive, resistant, and cliff-forming. In contrast with this, the

¹⁶ L. F. Noble, *A section of the Paleozoic formations of the Grand Canyon at the Bass Trail*, U. S. Geol. Surv. Prof. Paper 131, p. 27, 1922.

upper portion of the Toroweap formation is soft, crumbly, and slope-forming. The latter consistently undermines the former, causing, in many areas, vast ledges of the Kaibab to slump and give a deceiving appearance to the basal contact. Furthermore, the soft red beds and gypsum deposits of the upper Toroweap are usually well hidden beneath great mantles of talus.

As might logically be expected from the previous discussion, most of the evidences of unconformity between the Toroweap and Kaibab formations are found in the easternmost outcrops of these formations where the strata have a more nearly equal resistance to erosion and form continuous cliffs on the faces of which details of original structure are usually apparent. Evidence of the unconformity is to be seen in at least five widely separated localities. These are (1) in Black Box Canyon of the San Rafael River, Utah, (2) in Badger Canyon near Lees Ferry, Arizona, (3) along the Little Colorado Canyon, (4) at Hilltop near Havasu Canyon, and (5) near the base of Fossil Mountain in Grand Canyon, Arizona. South of Flagstaff, Arizona, in places where the Toroweap formation does not occur, the pre-Kaibab unconformity involves erosion in the underlying Coconino sandstone. This has been noted at Mack's Crossing on East Clear Creek, at Clover Creek, at Pivot Canyon, and elsewhere.

Evidence at San Rafael Swell, Utah

Following his studies of the San Rafael Swell, Utah, Gilluly states that "the relations of the Kaibab limestone to the [underlying] sandstone are not clear."¹⁷ He points to the conglomeratic nature of the cherty sandstone and thin shale in one or two localities and to his observation that characteristic joint sets in the sandstone do not continue up into the limestone as suggestive of unconformity. He concludes, however, that inasmuch as these features might be explained in more than one way, they should not be regarded as proof that a break in sedimentation preceded the Kaibab deposition.

In parts of the San Rafael Swell visited by the writer during November 1935, those features noted by Gilluly as suggesting unconformity were not found. Certain other features were observed, however, that clearly indicate the presence of a hiatus between beds of the Kaibab formation and the underlying cliff-forming sandstone. Along the rims of Black Box Canyon, at the eastern end, a gentle warping of the underlying beds is clearly shown by the 15 or more feet of non-cross-bedded sandstones which occur at the top (plate 11a). A surface of slight relief had been developed when sediments of the Kaibab formation were first deposited, so that today the lower beds of the Kaibab (in some places all of them) fill depressions and bank against small hills as shown in figure 8.

¹⁷ James Gilluly, *Geology and oil and gas prospects of part of the San Rafael Swell, Utah*, U. S. Geol. Surv. Bull. 806, p. 81, 1929.

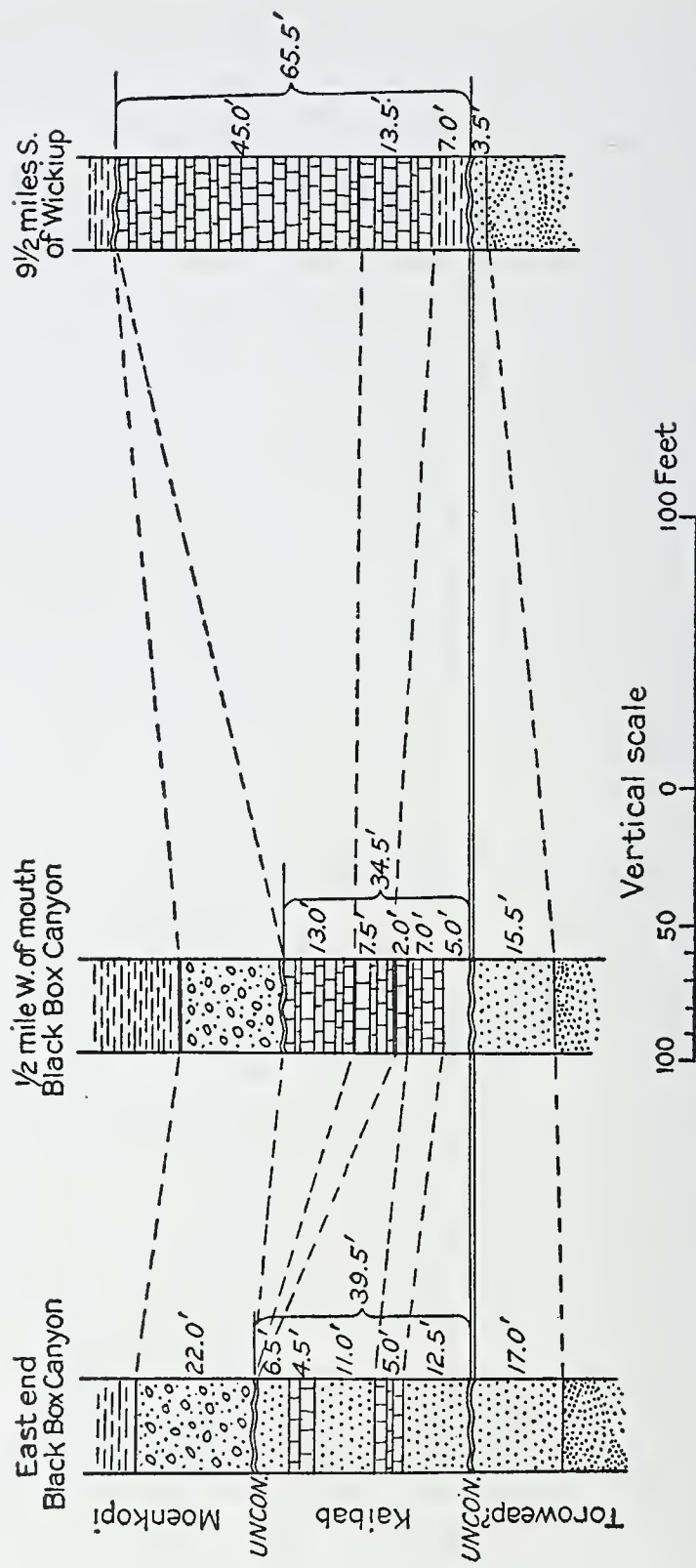


FIG. 8. Comparative sections of Kaibab formation in San Rafael Swell, Utah

Inasmuch as the undulations in the strata below the unconformity noted in Black Box Canyon cannot be traced downward owing to the cross-bedded character of the main sandstone mass, there is a possibility that the topmost beds are undulatory not because of warping but as a result of original deposition on a hilly surface developed by erosion of the cross-bedded sandstones. This possibility seems unlikely, however, because the top sandstone beds maintain a rather constant thickness throughout, i. e., in depressions and on the sides and tops of hills. Furthermore, unquestionable examples of warping or deformation in beds of the Toroweap formation, immediately below the Kaibab, have been noted elsewhere, so it is logical to infer a similar explanation in the San Rafael locality.

Evidence in Canyon Eight Miles Southwest of Lees Ferry, Arizona

In the deep canyon tributary to Marble Gorge at a place nearly opposite Badger Canyon, Arizona, there is a remarkably fine demonstration of the unconformity between the Kaibab formation and the underlying Toroweap. Evidence here consists of both a plainly visible surface of relief developed at the top of the Toroweap formation and an exceptional display of angular conglomerate.

Evidences of the irregularity of the surface on which basal beds of the Kaibab formation were deposited are seen in a number of places along the walls of the gorge opposite Badger Canyon (plate 11c). The maximum amount of relief noted was 26 feet, at a place where the gnarly-bedded sandstone of the Toroweap stood as a mound projecting through the lowermost sandstone and well into the limestone beds of the Kaibab. It is difficult to deduce the exact significance of the irregular surface referred to above. In places it appears to be a direct result of the extremely gnarly type of bedding which is so highly developed in the upper sandstone of the Toroweap in this area. Whether or not any of the irregularities were formed by local crumpling of the Toroweap surface could not be determined, but numerous examples suggest a brief period of active pre-Kaibab erosion.

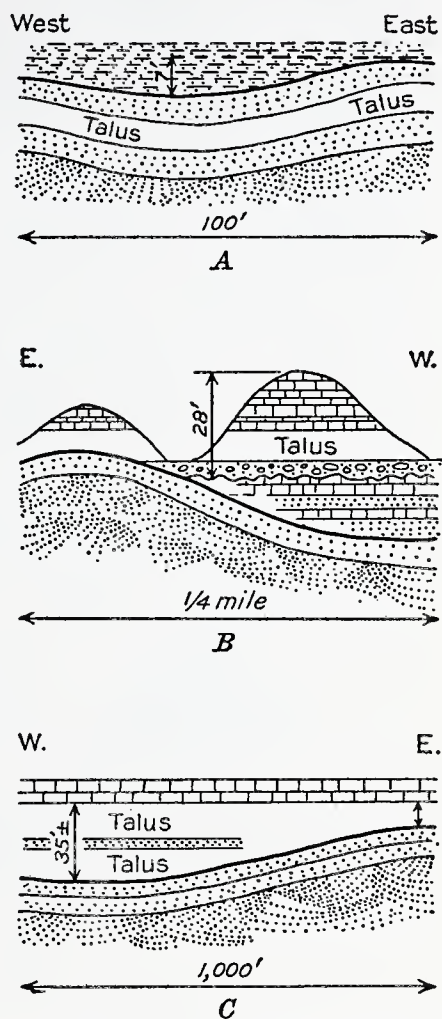


FIG. 9. Unconformity at base of Kaibab formation in San Rafael Swell, Utah

- A. North side, east end, Black Box Canyon
- B. South side, east end, Black Box Canyon
- C. North side, east central, Black Box Canyon

The boulders at the top of the Toroweap formation are conspicuous features both because of the huge size of some and because of the bright contrasting colors of most of them. The boulders are more or less angular and some are as large as 4 feet in diameter (plate 10a). The principal types of rock represented in the conglomerate are: (1) yellow, calcareous sandstone, (2) chocolate-brown mudrock, (3) fine-grained, pale green sandstone, (4) purple sandstone, and (5) small red quartz pebbles. In the sedimentary types, the bedding is not oriented but stands in every direction.

Any satisfactory attempt to interpret the meaning of the angular conglomerates at the top of the Toroweap formation near Badger Canyon must account not only for the size and angularity of the boulders, but also for the fact that their margins are irregular and weakly developed and that they are embedded in a matrix precisely similar to the upper sandstone of the Toroweap formation in this area. These features suggest that the boulders were transported only short distances and that consolidation had barely been attained before erosion set in.

Evidence in Little Colorado Canyon, Arizona

Along the sheer walls of the Little Colorado Canyon east of Waterloo Hill, evidences of unconformity between the Kaibab and Toroweap formations are found in numerous places. In this area the basal Kaibab is a massive impure limestone, while the underlying Toroweap consists of from 6 to 40 feet of fairly resistant gnarly-bedded sandstone at the base of which is the same type of red, flat-bedded sandstone found farther west in Grand Canyon. The sandstone beds of the Toroweap formation are undulatory and their upper surfaces appear to have been truncated before the flat-lying basal beds of the Kaibab were deposited (plate 11b).

Because of the highly cross-bedded character of the Coconino sandstone as seen in the walls of the Little Colorado gorge, it is impossible to determine whether or not an undulatory surface, comparable with that displayed in the Toroweap sandstones, is reflected below. For this reason it is impossible to ascertain whether the undulations in the Toroweap beds are the result of a gentle warping during a slight regional uplift or represent original slopes of deposition on an irregular surface of the Coconino sandstone. The writer is strongly inclined to the former explanation: first, because the beds retain uniform thickness throughout the undulations; second, because a slight uplift, local or regional, is implied by the truncation of the tops of the beds to a flat surface; lastly, because evidence of unconformity at the top of the Coconino, such as would be necessary to form depressions of the type found, is completely lacking in other localities.

Evidence at Fossil Mountain in Grand Canyon

At the south end of Fossil Mountain in Grand Canyon, Arizona, the *Schizodus* limestone¹⁸ and a few ledges of impure limestone above occur at

¹⁸ A thin persistent limestone which contains dozens of pelecypods of the genus *Schizodus* per square foot and which is a marker bed throughout much of the Grand Canyon area.

the top of the Toroweap formation and are overlain by a calcareous sandstone of the Kaibab formation containing quartzitic concretions and abundant silicified shells and molds of *Chonetes kaibabensis*.

On Fossil Mountain, a few feet below the base and in front of the ledges of *Schizodus* limestone, occurs a deposit of angular conglomerate (plate 10c). This is the "breccia" which, as previously stated (page 28), was recorded by Noble at the base of his subdivision B. The boulders are of many sizes, ranging up to 3 or 4 feet in diameter, and they show no signs of rounding. Many are limestone slabs which probably broke off from ledges near by and so were transported only a short distance. Included in the fragments are some from the *Schizodus* limestone showing its typical fossils; however, none which might be referred to the Kaibab have been found. All the boulders are well consolidated, and they are embedded in a yellow, crumbly sandstone which shows no evidence of bedding.

The Fossil Mountain section is separated from the corresponding section on the neighboring promontory to the southeast by a valley about an eighth of a mile wide which has been formed by recent erosion. In the section on the promontory the contact between the Kaibab and Toroweap for-

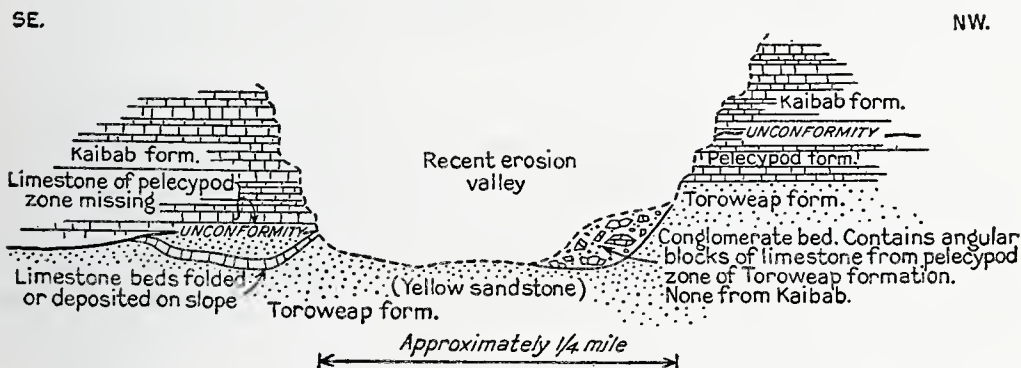


FIG. 10. Unconformity between Kaibab and Toroweap formations at Fossil Mountain, Grand Canyon

mations is definitely at a lower level than on Fossil Mountain. This is not due to faulting in the area between the localities but to the fact that the *Schizodus* and overlying limestones in the upper part of the Toroweap formation are missing. In brief, pre-Kaibab erosion has at this point lowered the level on which the basal Kaibab beds were deposited. It is also significant that the remaining resistant beds in the top of the Toroweap formation are warped to form a shallow syncline (figure 10) in this locality.

Evidence at Hilltop near Havasu Canyon, Arizona

On the hillsides above the Havasupai Indian warehouse at Hilltop, the contact between the Kaibab and Toroweap formations is largely obscured by talus which covers the friable red beds and gypsum deposits at the top of the latter formation. At one place on the north side, however, evidence of unconformity between these two formations is clearly visible. *Schizodus*

and other impure limestone beds near the top of the Toroweap formation are warped and in part removed in the erosion of a channel which is filled with the basal sandstone deposits of the Kaibab formation (figure 11 and plate 10*b*).

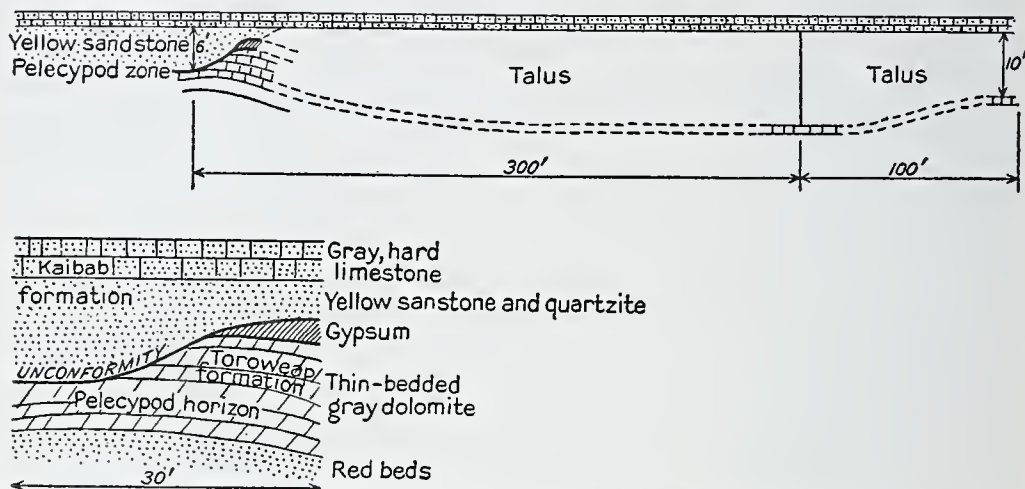


FIG. 11. Unconformity between Kaibab and Toroweap formations at Hilltop, Havasu Canyon

Evidence on Mogollon Plateau South of Flagstaff

On the Mogollon Plateau south and east of Flagstaff the resistant Kaibab formation forms the surface rock except where covered with recent lavas. In numerous places deep canyons have dissected this plateau and have shown that the Coconino sandstone, and not the Toroweap formation, underlies the Kaibab. The area lies south and east of the basin of deposition in which the Toroweap was formed, hence its absence here is explained by lack of deposition rather than by subsequent erosion.

Although extensive outcrops showing the contact between the Kaibab formation and the Coconino sandstone are scarce on the well-forested Mogollon Plateau, evidence of pre-Kaibab unconformity has been found there in several places. In a previous paper¹⁹ the writer described an outcrop 15 miles south of Flagstaff, Arizona, where the top of the Coconino sandstone appears to have been scoured on a small scale and the resulting depressions to have been filled with sandy limestone of the Kaibab formation. In Chevelon Canyon, about 25 miles south of Winslow, and likewise at Mack's Crossing on East Clear Creek, similar observations have subsequently been made.

Near Clover Creek, 0.5 mile west of the Flagstaff-Pine road, and in Pivot Canyon below the crossing of the same road, a surface of erosion at the top of the Coconino sandstone could not be observed in the limited exposures, but in both localities the presence of an unconformity was suggested by measurements in comparative sections. Near Clover Creek the thickness of

¹⁹ Edwin D. McKee, *The Coconino sandstone—its history and origin*, Carnegie Inst. Wash. Pub. No. 440, VII, p. 88, 1934.

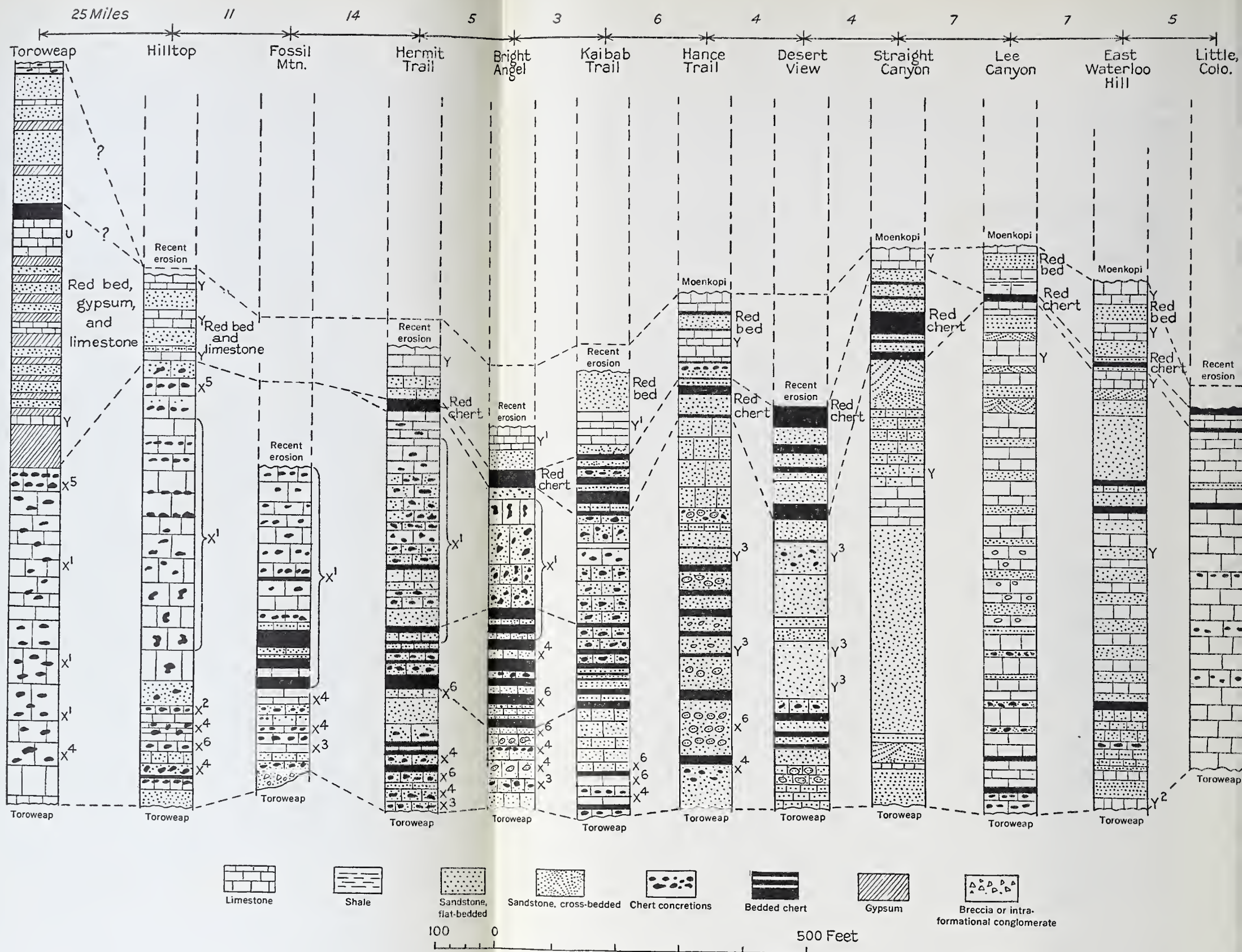


FIG. 12. West-east sections of Kaibab formation

X = Fauna of marine type I or "*Productus bassi*" fauna

X¹ = *Productus bassi*, ± *Meekella*, *Squamularia*, *Spiriferina*, *Avonia*, *Pugnoides*, *Derbya*, *Chonetes subliratus*, *Composita*, *Lophophyllum*, bryozoa, crinoids, et al.

X² = *Productus bassi*, ± crinoids, *Archæocidaris*, bryozoa

X³ = Crinoids, ± *Archæocidaris*

X⁴ = *Chonetes kaibabensis*, crinoids, ± *Productus bassi*

X⁵ = *Productus bassi*, ± *Productus occidentalis*, *Archæocidaris*, *Spiriferina*

X⁶ = *Productus bassi* only

Y = Fauna of pelecypods and gastropods undetermined; "*Bellerophon*" fauna

Y¹ = *Bellerophon*, *Allorisma*, *Schizodus*, *Pleurotomaria*, *Ditomopyge*, *Nucula*, *Astartella*, *Pleurophorus*, et al.

Y² = *Bellerophon*, *Schizodus*, *Dentalium*

Y³ = Desert View facies (facies 3 of β member)

Y⁴ = *Schizodus* only

U = Fauna of mixed marine and brackish-water types

Euomphalus, *Composita*, *Productus bassi*, crinoids, bryozoa (facies 1 of α member)

the "pelecypod" limestone beds, between the top of the Coconino and the base of the brachiopod-bearing limestone, ranged from 28.5 feet to 42.5 feet on the two sides of the canyon, that is, in a distance of about 200 yards. In Pivot Canyon measurements made of the same limestone unit at outcrops about a mile apart showed also a difference of 12.5 feet in thickness. The range in both cases might be attributed to difference in amount of material deposited; however, considering the nature of the deposits and the short distances between sections, especially in the Clover Creek locality, it seems far more probable that an uneven surface on which Kaibab deposition began explains the variation in thickness of the lower limestone unit.

Conclusions Concerning Kaibab-Toroweap Unconformity

A consideration of the various types of evidence cited above clearly indicates the presence of an unconformity between the Kaibab and Toroweap formations and, where the latter is missing, between the Kaibab formation and Coconino sandstone. The unconformity apparently is of a widespread, regional nature and involves a slight deformation of the area (though probably not much uplift) as indicated by local warping and bending of resistant beds. As a result, erosion on a small scale left its marks in numerous places, not in the form of extensive removal of beds, but in local channeling or in planing of the surface irregularities. At no place yet known is there evidence of either intense deformation or strong erosion during the post-Toroweap-pre-Kaibab interval.

That the duration of the Toroweap-Kaibab hiatus probably was not great is shown by the slight consolidation of the boulders in the angular conglomerate near Badger Canyon.²⁰ A short interval is indicated also by faunas in the limestones of these two formations, for, although definitely different, they have much in common.

FACIES OF THE KAIBAB FORMATION

Based on approximately fifty measured sections, a classification has been developed embodying the principal divisions of the Kaibab formation, and presenting a good picture of the conditions represented by each, together with their interrelationships. The formation is divided vertically into three members, designated as α , β , and γ , from top to bottom. These members are best characterized as (α) the time of receding sea, (β) the time of most extended sea, and (γ) the time of advancing sea. The α or uppermost of these has long been recognized as distinctive by workers in the region and has variously been referred to as the A member, the Super Aubrey, the Bellerophon limestone, and the Harrisburg gypsiferous member. The middle division, commonly termed the "cherty limestone," is the B member of most earlier writers, while the γ or lowermost member is local in distribution, having been recognized only on the Mogollon Plateau south of Flagstaff. It is unrecorded in earlier literature.

²⁰ In contrast, the limestone slabs in the "breccia" at Fossil Mountain were completely developed by the time of breaking and redepositing.

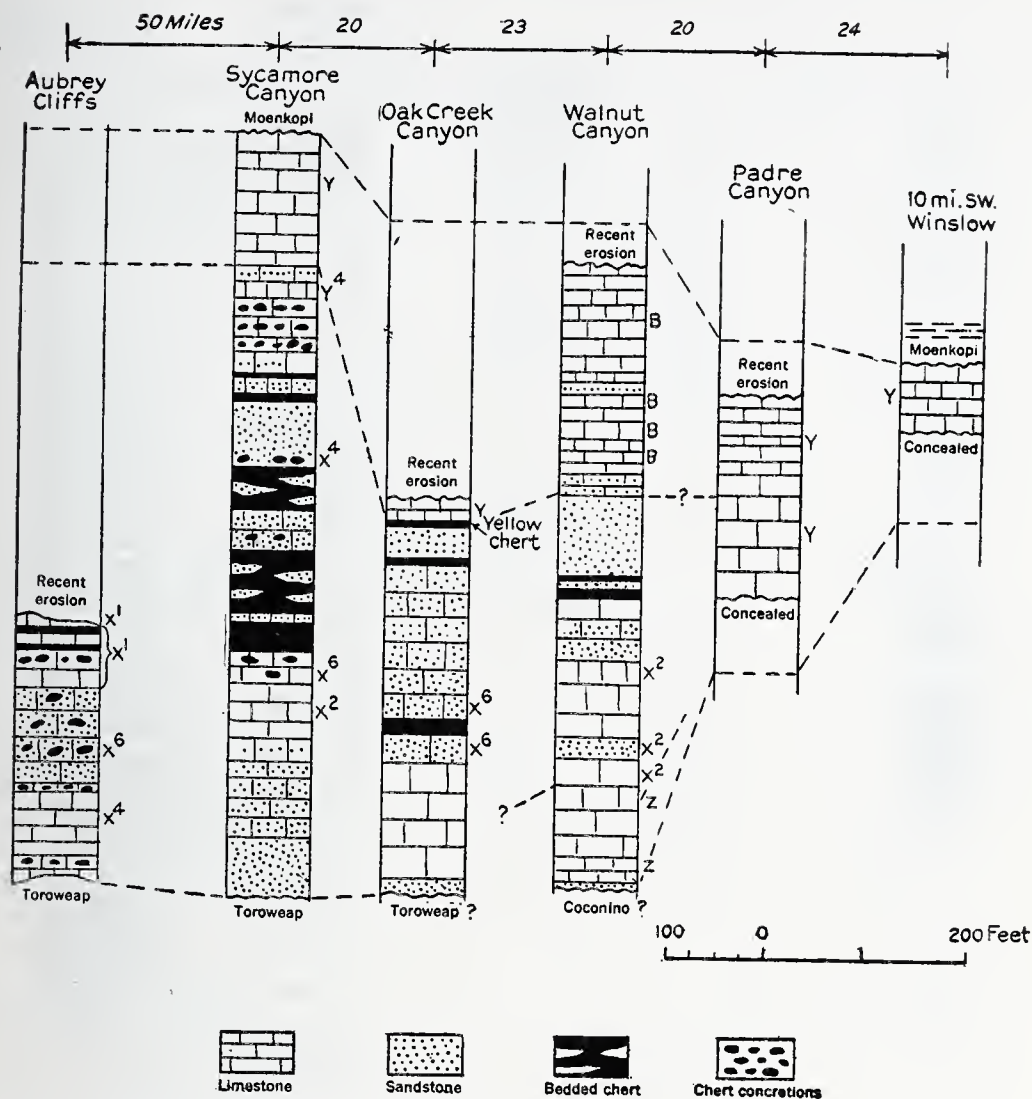


FIG. 14. West-east sections of Kaibab formation

X = Fauna of marine type I or "*Productus bassi*" fauna

X¹ = *Productus bassi*, ± *Squamularia*, *Avonia*, crinoids, *Productus occidentalis*, *Derbya*, *Waagenoconcha*, *Spiriferina*, *Chonetes subiliratus*, *Aviculopecten*, et al.

X² = *Productus bassi*, ± crinoids, *Archæocidaris*, bryozoa

X⁴ = *Chonetes kaibabensis*, crinoids, ± *Productus bassi*

X⁶ = *Productus bassi* only

Y = Fauna of pelecypods and gastropods undetermined; "*Bellerophon*" fauna

Y¹ = *Schizodus* only

Z = Fauna of pelecypods and gastropods, large forms of γ member

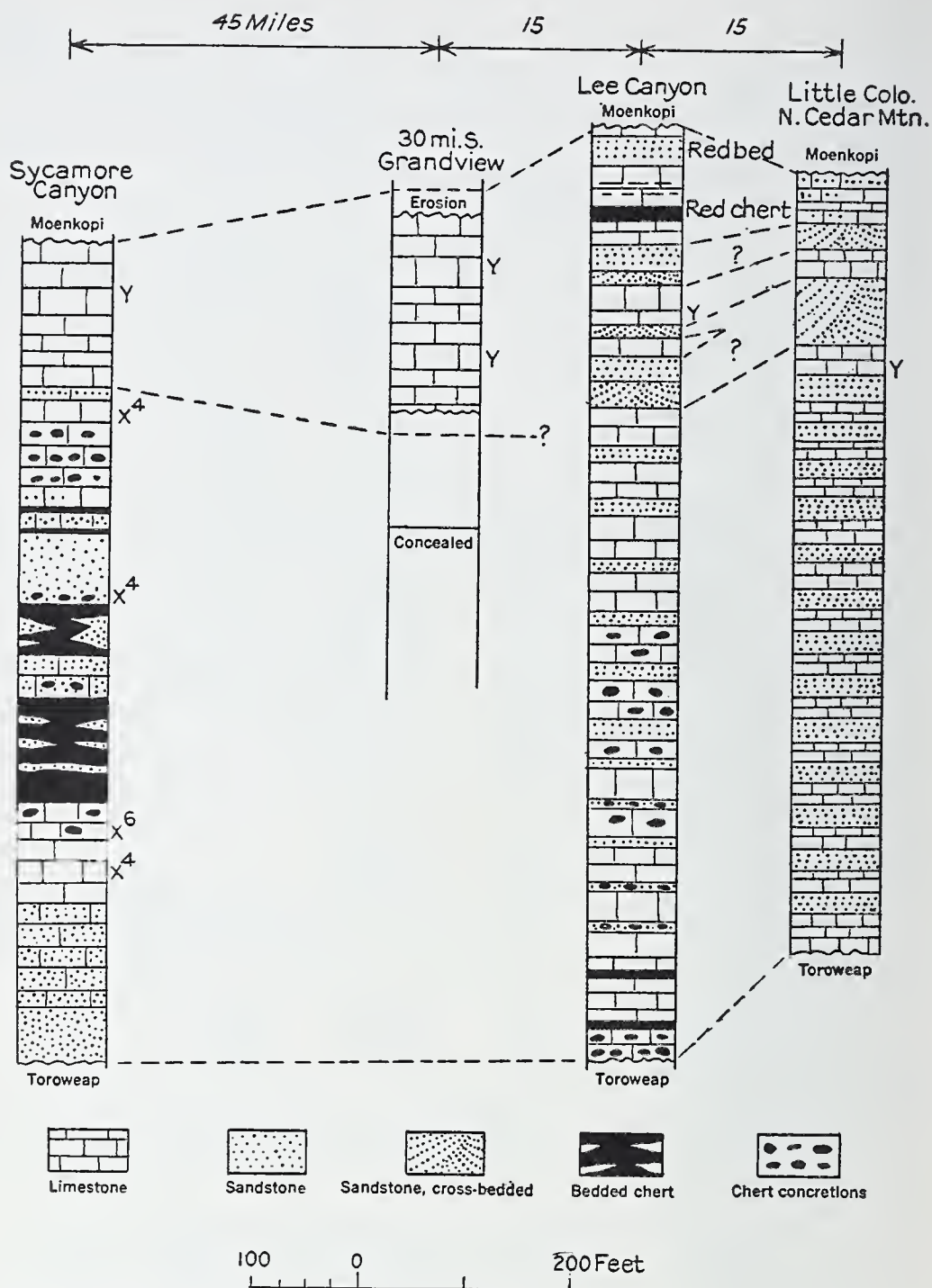


FIG. 15. South-north sections of Kaibab formation

X = Fauna of marine type I or "*Productus bassi*" faunaX² = *Productus bassi*, ± crinoids, *Archæocidaris*, bryozoaX⁴ = *Chonetes kaibabensis*, crinoids, ± *Productus bassi*X⁶ = *Productus bassi* onlyY = Fauna of pelecypods and gastropods undetermined; "*Bellerophon*" faunaY⁴ = *Schizodus* only

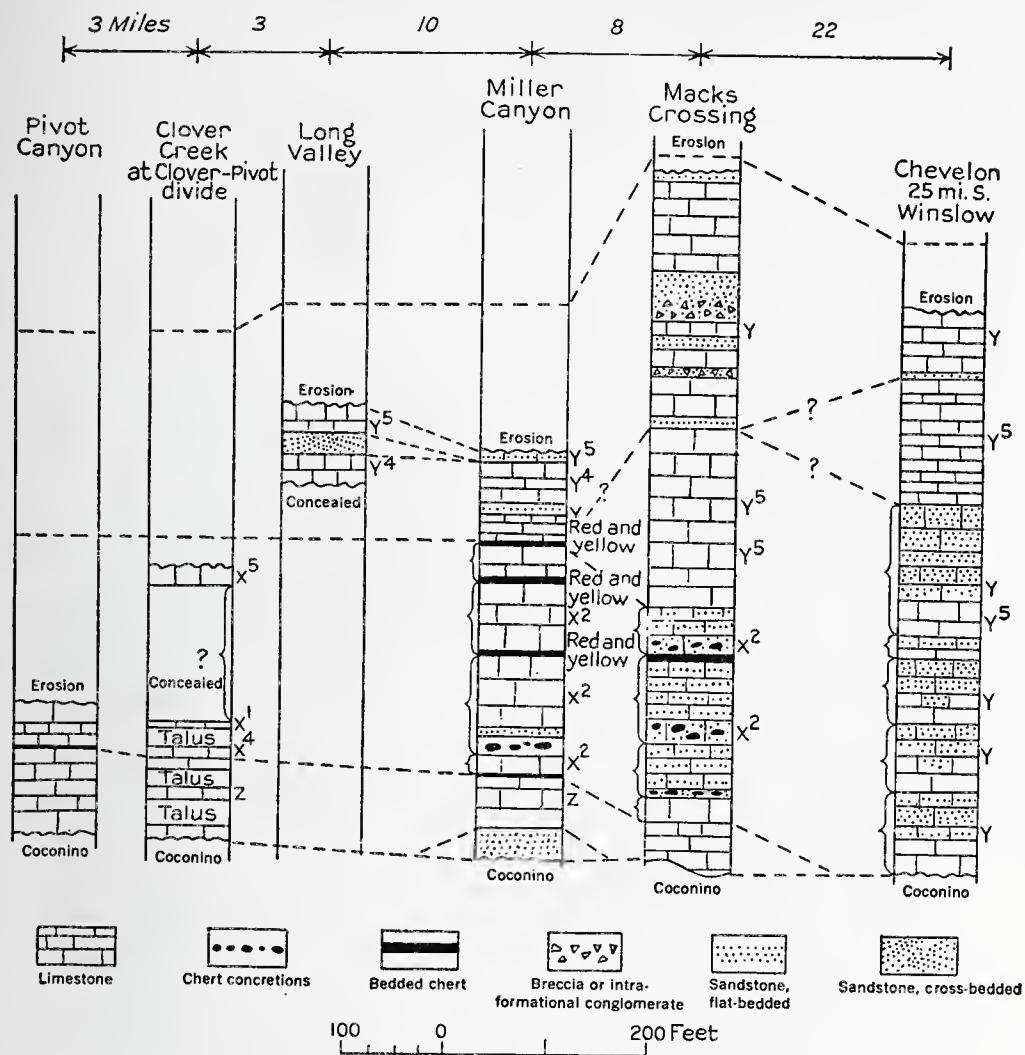


FIG. 16. West-east sections of Kaibab formation

X = Fauna of marine type I or "*Productus bassi*" fauna

X¹ = *Productus bassi*, ± *Meekella*, *Composita*, *Avonia*, *Squamularia*, *Derbya*, *Pugnoides*, et al.

X² = *Productus bassi*, ± crinoids, *Archæocidaris*, bryozoa

X⁴ = *Chonetes kaibabensis*, crinoids, ± *Productus bassi*

Y = Fauna of pelecypods and gastropods undetermined; "*Bellerophon*" fauna

Y⁴ = *Schizodus* only

Y⁵ = Like Y + *Productus bassi*

Z = Fauna of pelecypods and gastropods, large forms of γ member

{ = Sedimentary cycle

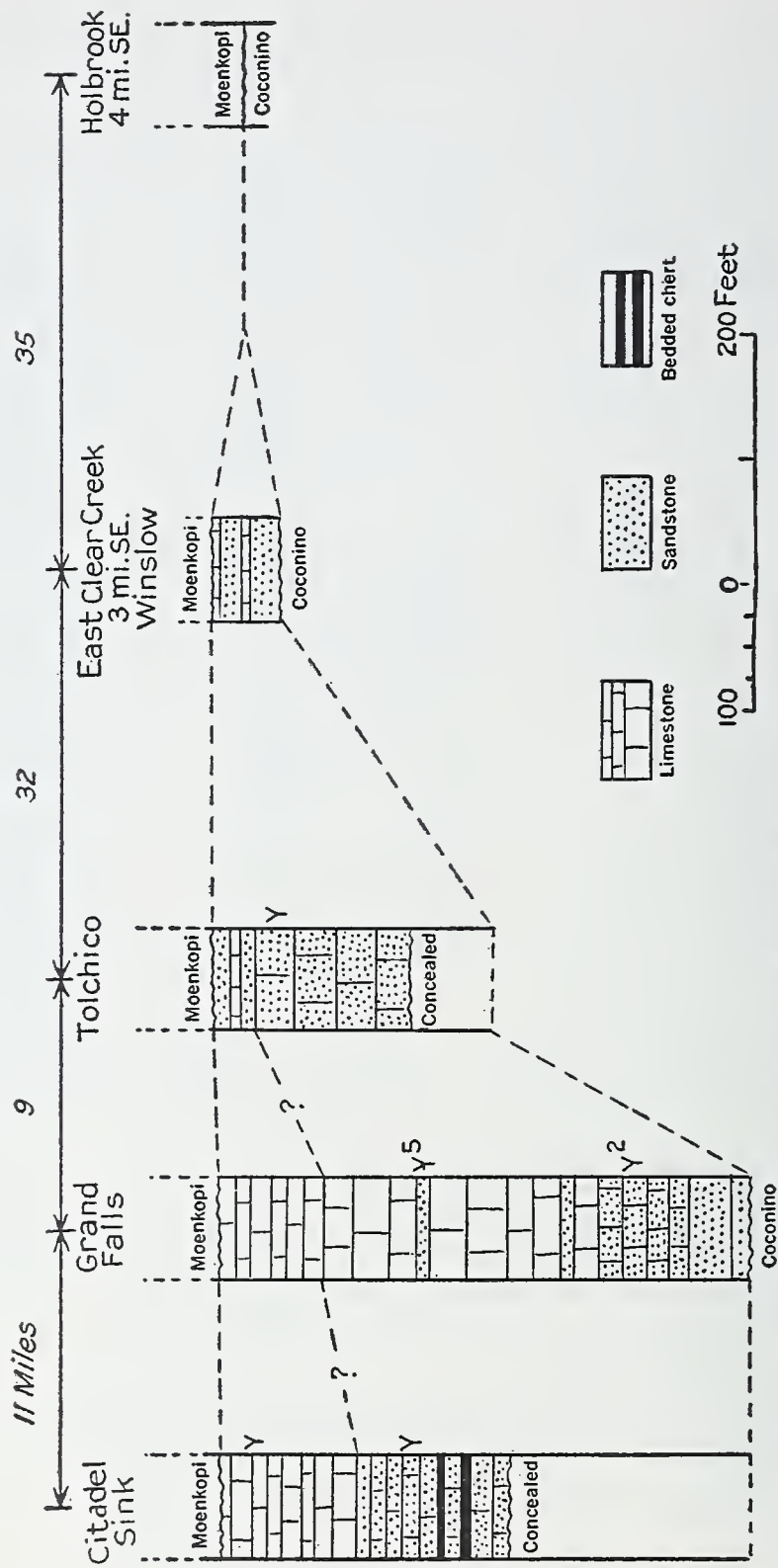


FIG. 17. Northwest-southeast sections of Kaibab formation
Y = Fauna of pelecypods and gastropods undetermined; "Bellerophon" fauna
Y² = *Bellerophon*, *Schizodus*, *Dentalium*
Y⁵ = Like Y + *Productus bassi*

Within each of the upper two members of the Kaibab formation, horizontal variations both in lithologic character and in fauna are numerous. To designate these, a division of members into facies is proposed, the plan of which classification is summarized in table 4. It is very probable that

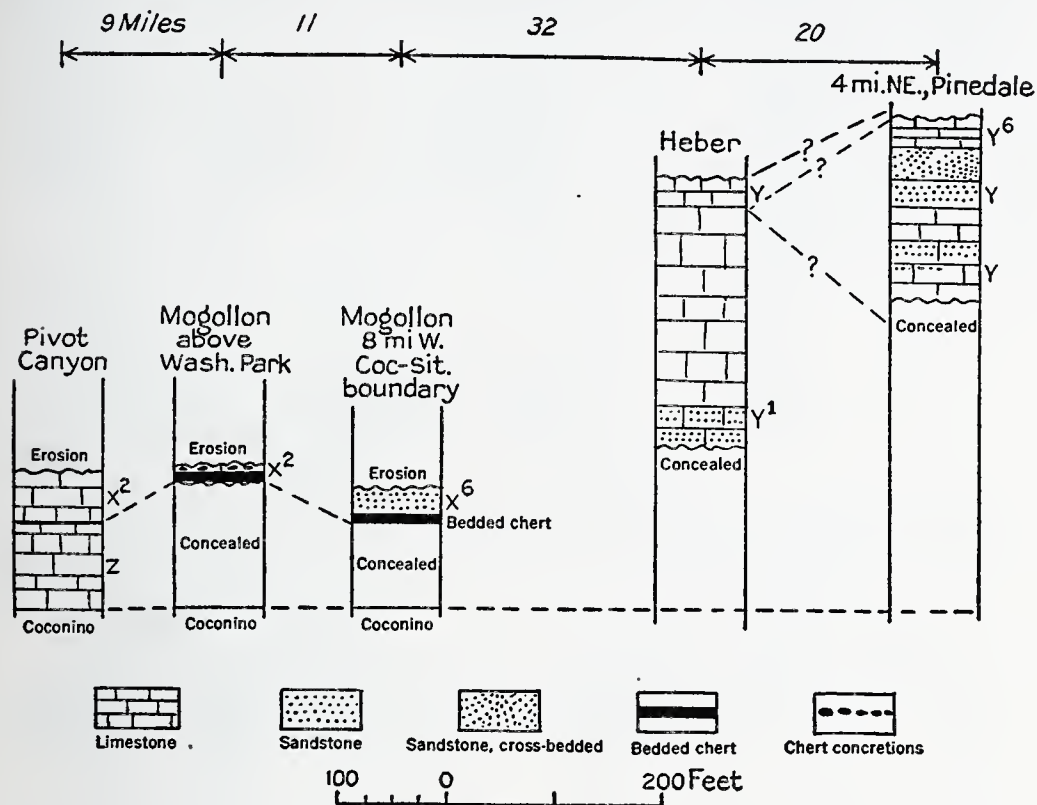


FIG. 18. West-east sections of Kaibab formation

X = Fauna of marine type I or "*Productus bassi*" fauna

X² = *Productus bassi*, ± crinoids, *Archæocidaris*, bryozoa

X⁶ = *Productus bassi* only

Y = Fauna of pelecypods and gastropods undetermined; "*Bellerophon*" fauna

Y¹ = *Bellerophon*, *Allorisma*, *Astartella*, *Schizodus*

Y⁶ = *Euomphalus*

Z = Fauna of pelecypods and gastropods, large forms of γ member

more detailed studies of both faunas and lithologic characteristics will show the desirability of recognizing numerous additional facies and, in some instances, of splitting up those proposed here.

γ Member, Facies 1

In sections of the Kaibab formation on the Mogollon Plateau a series of fine-grained limestone beds, ranging in thickness up to 50 feet and bearing a unique fossil assemblage, is found at the base of the formation. The fauna consists almost entirely of mollusks, many of which are very large (see plate 12). Judging from the fauna and the nature of the limestone,

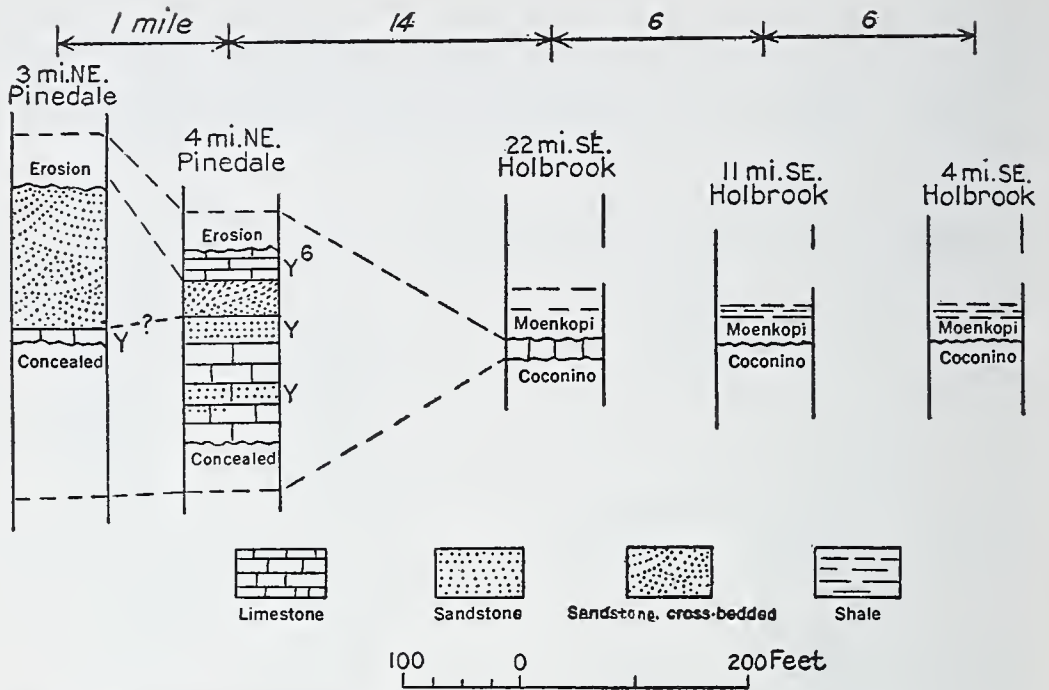


FIG. 19. South-north sections of Kaibab formation

Y = Fauna of pelecypods and gastropods undetermined; "*Bellerophon*" fauna
Y⁶ = *Euomphalus*

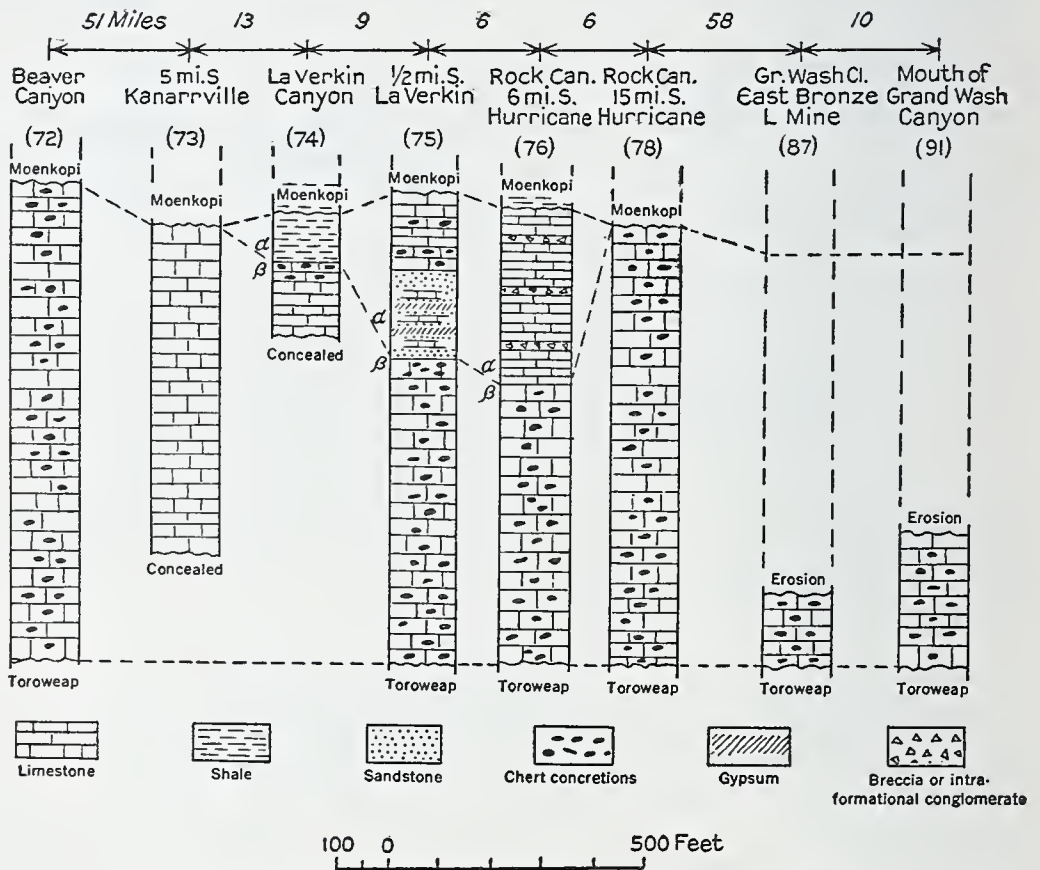


FIG. 20. North-south sections of Kaibab formation

Compiled from published sections by Lee, Huntington and Goldthwait, Reeside and Bassler, Longwell. Position of details within major rock units necessarily not accurate. Fossil zones not known. (Section numbers refer to base map and to list of published sections, page 9.)

TABLE 4. CLASSIFICATION OF UNITS IN KAIBAB FORMATION

Status	Environment—locality	Character	Other names—fauna
α member (upper).....	Time of receding seas	Thin-bedded limestones, chemical precipitates, red beds, local cross-bedded sandstones	Bellerophon limestone of Powell; Super Aubrey of Huntington and Goldthwait; Harrisburg gypsiferous member of Reeside and Bassler; subdivision A of Noble, 1927
Facies 1.....	Western area, i. e. Toroweap and westward	Alternating red beds, gypsum deposits, and thin-bedded limestones	Fauna mostly molluscan, some brachiopods (see plate 19)
Facies 2.....	Middle, eastern area, i. e. Hilltop to Little Colorado	Alternating thin-bedded limestones and red beds	Fauna molluscan (see plate 18)
Facies 3.....	Southern and southeastern areas, i. e. Sycamore Canyon east over Mogollon Plateau	Thin-bedded limestones in great thickness; locally sandstones, cross-bedded and flat-bedded, mostly light-colored	Fauna not well known but probably like preceding (see plates 19, 20)
Facies 4.....	Apparently restricted to area of Riney Jim Ranch between Flagstaff and Cameron	Massive magnesian limestone	Fauna molluscan, mostly gastropods (see plate 21)
Facies 5.....	San Rafael Swell, along Fremont River, Circle Cliffs	Thin-bedded, magnesian limestone	Fauna not well known; mostly molluscan; correlation tentative
β member (middle).....	Time of extended seas	Massive crystalline limestone, sandy limestone, and sandstone; in part with bedded and concretionary cherts	Subdivision A of Noble, 1922; subdivision B of Noble, 1927
Facies 1.....	Western area, i. e. from Hermit and Aubrey Cliffs west	Largely crystalline limestone, becoming sandy toward eastern border, concretionary chert abundant	Fauna of molluscoids, corals, and sponges (see plates 41-48)
Facies 2.....	East, central area, near Kaibab Trail and Sycamore Canyon	Sandy limestone and sandstone beds alternating with bedded cherts	No fauna except on borders, where species of adjoining facies appear
Facies 3.....	Middle, eastern area, i. e. Point Imperial, Desert View Point	Fine, uniform-grained, non-calcareous sandstone, brown	Fauna molluscan (see plate 15)
Facies 4.....	Eastern, southeastern, and southern areas, esp. on Mogollon Plateau, Little Colo. and Marble Canyons	Dolomitic limestones, in places sandy or alternating with sandstones	Fauna mostly molluscan (see plate 16)
Facies 5.....	San Rafael Swell, along Fremont River, Circle Cliffs	Sandstones, sandy limestones, and limestones	Fauna largely of molluscoids (see plate 16); correlation tentative
γ member (lower).....	Time of advancing seas	Massive and thin-bedded, impure limestones	
Facies 1.....	Southern and southeastern area, i. e. on Mogollon Plateau	Magnesian limestones with sandy limestones	Fauna of large mollusks (see plate 12); confined to Mogollon Plateau

this facies represents not a normal marine environment, but one of localized, probably brackish-water conditions. In every locality where it has been

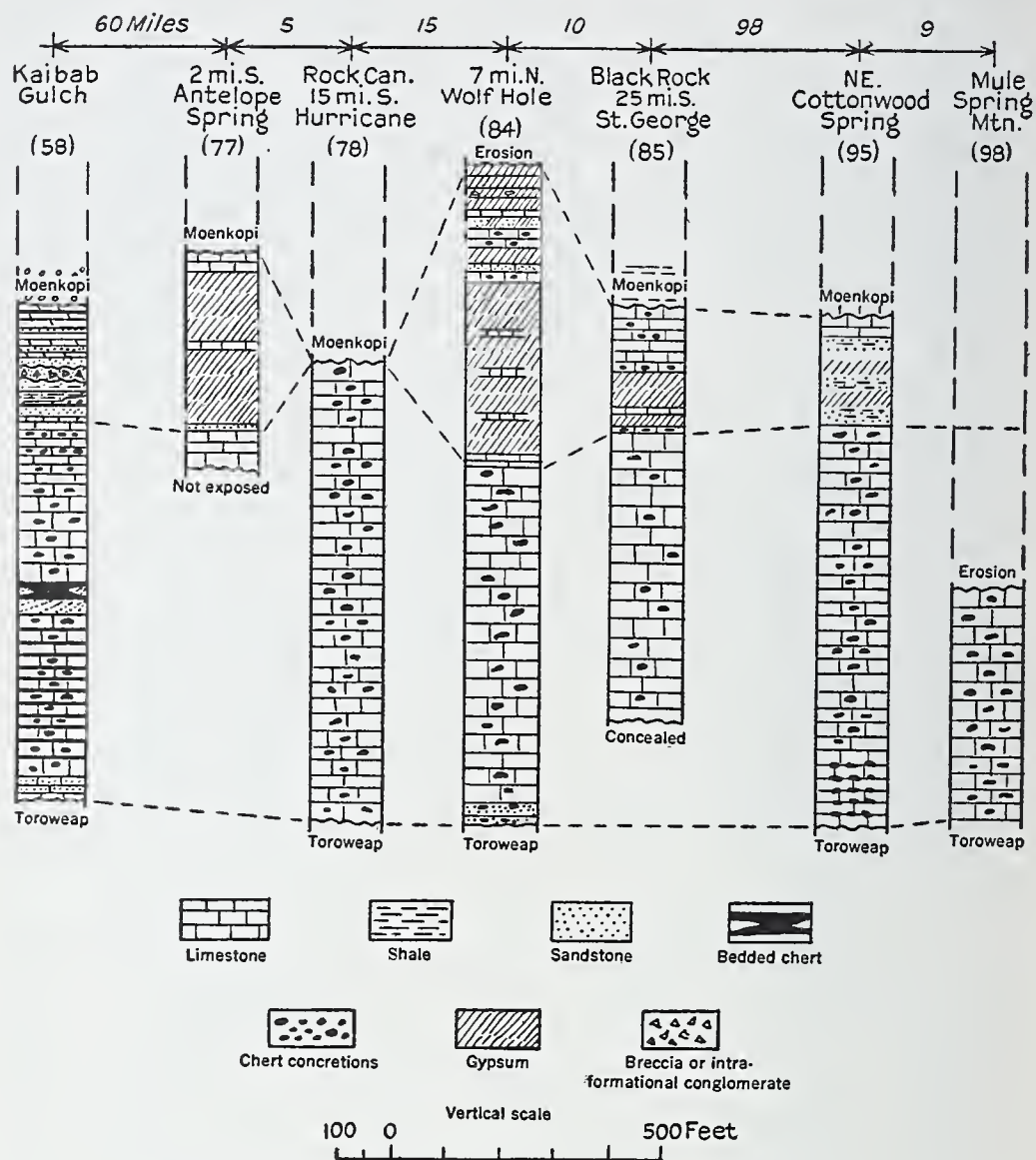


FIG. 21. East-west sections of Kaibab formation

Compiled from published sections by Noble, Reeside and Bassler, Longwell, Hewitt. Position of details within major rock units necessarily not accurate. Fossil zones not known. (Section numbers refer to base map and to list of published sections, page 9.)

recognized, it was found to be overlain by limestones of the β member which are sandy, in part cherty, and characterized by a marine fauna composed largely of brachiopods and echinoids. It seems logical to conclude, therefore, that the γ member was developed locally in a basin with a specialized environment, nearly or entirely cut off from the main sea, and that later the character of this area was changed with an advance of the sea from the west and south bringing normal marine conditions.

β Member, Facies 1

Sediments and faunas that apparently were developed in the open sea, under normal marine conditions, are classified as facies 1 of the β member

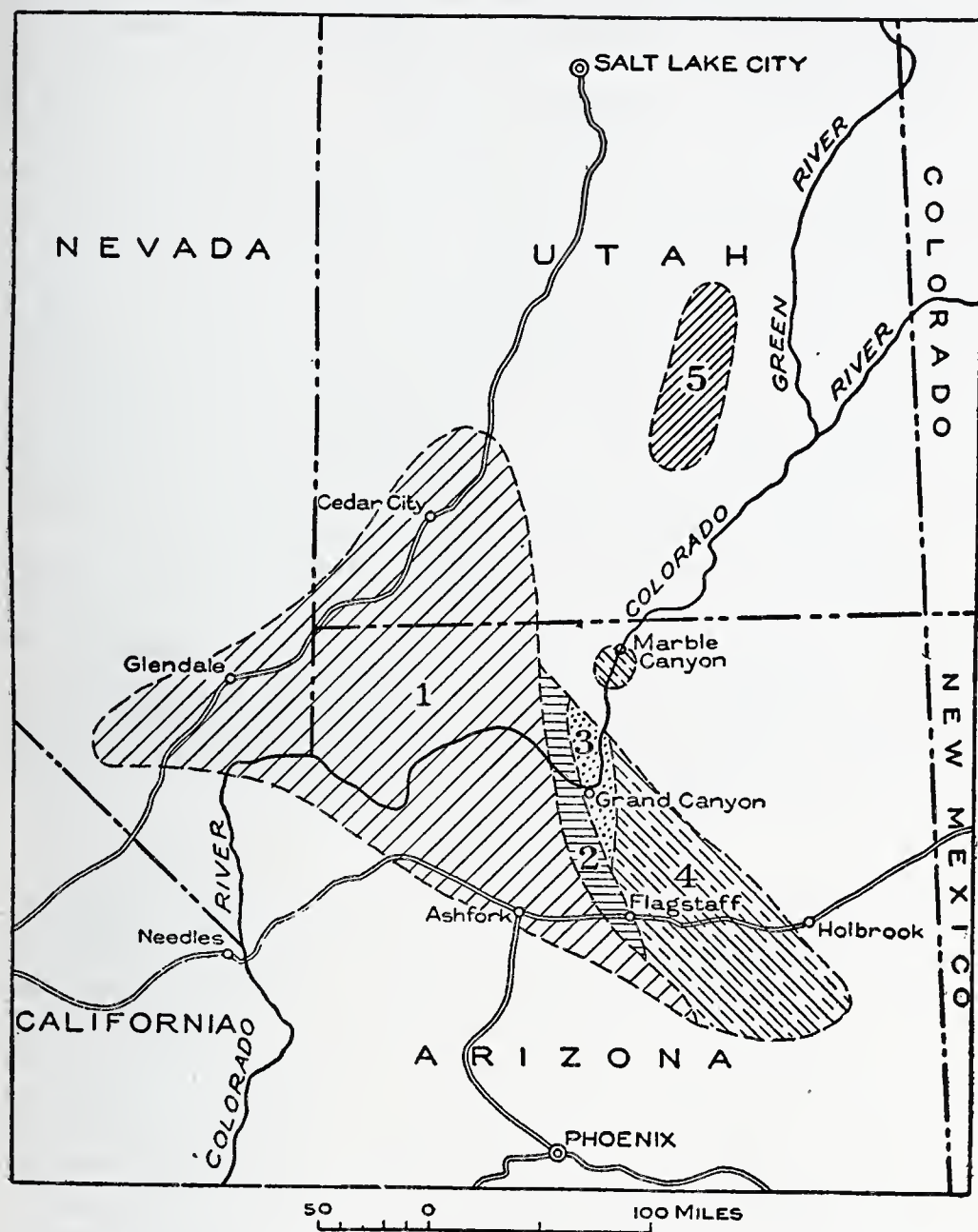


FIG. 22. Map showing distribution of facies comprising β member of Kaibab formation

or time of most extended sea. To this facies have been referred rocks which cover fully 75 per cent of the known area of exposure of the formation as illustrated by the distributional map (figure 22). They extend from the westernmost known exposures, which are in Nevada, eastward and south-eastward to the vicinity of Hermit Trail in Grand Canyon and to the west-

ern part of the Mogollon Plateau farther south. The limestone is typically light gray, coarsely crystalline, and, in places, largely composed of marine organisms as illustrated by plate 13a. As might be expected, toward the east, or shoreward, clastic grains appear and become increasingly numerous in the limestone until the entire character of the rock is changed and a new facies appears.

Chert in facies 1 of the β member is abundant. It occurs in the form of hard round concretions and irregular nodules of various types, colors, and sizes. Bedded cherts are lacking, although in places the nodules have lined up in definite bands or are concentrated in certain horizons, especially toward the shoreward margin of the facies. In general, the rather uniform character of the massive crystalline limestone and the broad distribution of the chert scattered throughout it are features of all sections from Hilltop (Havasu Canyon) westward, and present a marked contrast with the bedded cherts and intermediate beds of sandy limestone farther east. Essentially all the chert is thought to have been deposited on the sea bottom, and the distribution of much of it apparently has been controlled by organisms, as indicated by sponge structures in the centers of concretions. A detailed discussion of these cherts is given in chapter III.

The fauna of facies 1 is the typical open-sea fauna of the Kaibab formation, consisting of brachiopods, horn corals, bryozoans, pelecypods of the pecten group, and crinoids. It might be referred to as the *Productus bassi* fauna, as the species of that name is by far the most abundant and generally distributed throughout the facies. The principal species found associated are illustrated in plates 41 to 48, but further discussion of their significance is reserved for the chapter on stratigraphy (chapter V).

β Member, Facies 2

From a geographical standpoint facies 2 of the β member is a long, narrow strip bordering the open-sea facies on its shoreward side. Sediments characteristic of facies 2 extend north and south, passing through Grand Canyon in the vicinity of Bright Angel and Kaibab Trails, and are represented in Sycamore Canyon to the south (see map, figure 22). Lithologically this facies consists of chert interbedded with alternate layers of very sandy limestone (plate 13c). Toward the east the sandy limestone merges into pure sandstone, but in the opposite direction it grades into the typical coarsely crystalline limestone of facies 1. The bedded chert is believed by the writer to have been formed on the sea floor, deposited from waters containing much silica in an area where stream waters mingled with marine. The evidence in support of this theory is presented in the discussion of cherts in chapter III.

The fauna of facies 2 is not distinctive. Since it occupies an area intermediate between that of pure lime deposition and that of pure sand, it contains on its borders fossils representing the more hardy species of both of

these environments. *Productus bassi*, crinoids, and, to a less extent, *Chonetes kaibabensis* are found to have extended their habitats from the open seas far into the area of facies 2 during certain stages of its deposition. In general, however, the rocks of this facies are barren of fossils, a plausible explanation for which is found in the probable high silica content of the waters in which deposition took place, as suggested by the extensive bedded cherts.

β Member, Facies 3

Tracing the strata of the β member eastward through the Grand Canyon to the vicinity of Desert View and Point Imperial, it is found that the sandy limestones and bedded cherts of facies 2 are replaced by brown or buff, uniformly fine-grained sandstones which are non-calcareous (plate 13d). These are designated as facies 3. In them is found a distinctive fauna consisting of numerous types of mollusks (plate 15).

From their physical composition, it is probable that the rocks of facies 3 were deposited near shore in an area where streams were supplying abundant clastic sediments. The generally fine and uniform character of these sediments suggests that the streams were sluggish in nature, having passed over a low, flat country. The character of the fossils indicates that the water was not of a normal marine type, but probably either brackish or relatively fresh.

The environment represented by facies 3 was very limited, as indicated on the map (figure 22). Over a wide area, it is replaced as a near-shore phase of the β member by the magnesian, "brackish water" limestones of facies 4. This distribution of facies and the relation of one to the other apparently substantiates the theory that river waters emptying into the sea supplied both the clastic sediments of facies 3 and also the silica of the bedded cherts in facies 2, which occurs farther from shore in the same area. Elsewhere along the marginal area, impure limestones of facies 4 were forming in partially landlocked waters where dwelt distinctive molluscan faunas.

β Member, Facies 4

Facies 4 is represented by a large portion of the near-shore sediments of the β member. It includes a number of sedimentary types and it shows considerable variation over the area. The only features common to all sections in this facies are the dominantly impure, fine-grained character of the dolomitic limestones and the preponderance of mollusks among the fossils. In general the beds of this facies are more massive than those of the overlying α member, which is also impure and highly magnesian.

It is probable that, after more detailed analyses of the sedimentary units and a careful study of fossils from each part, it will be found desirable to recognize several distinctive facies within the present facies 4. In some sections the limestone is sandy; elsewhere it is fairly free of clastics but

occurs interbedded with sandstones. Lack of extensive collections and the poor state of preservation of the fossils make it difficult to illustrate the assemblage or assemblages that characterize this facies, although *Bellerophon* and *Schizodus* are common in most sections (plate 16).

β Member, Facies 5

In the San Rafael Swell, along the Fremont River, and in the Circle Cliffs of southeastern Utah occur Permian limestones and sandstones which, because of their stratigraphic position above cross-bedded white sandstone and at the top of the Paleozoic series, have been referred to the Kaibab formation. As no Permian rocks are exposed for a distance of approximately 70 miles southwestward from Circle Cliffs, it is impossible to demonstrate the relationship between these strata and those at Badger Canyon, which unquestionably belong to the Kaibab formation.

Lithologically the southeastern Utah strata that have been referred to the Kaibab formation embrace a wide range in character. The principal types represented are magnesian limestones with and without nodular chert, sandy limestones, and sandstones. A typical sample of sandy, fine-grained limestone from a brachiopod-bearing zone in San Rafael Swell is shown in plate 14c. None of the sequences of strata shows any close resemblance to those of the various facies found farther south.

Although the writer was unable to collect many fossils from the Kaibab formation of the Circle Cliffs area, extensive collections have been made by R. C. Moore and reported on by Girty.²¹ According to the latter, these are definitely "Permian and show more or less close faunal affinities to the Kaibab limestone." Unfortunately, however, the preservation of the material was unfavorable for exact identification, and since many of the species and genera were new, precise correlation was impossible. The faunal lists given by Girty show a great preponderance of mollusks, but Moore states that numerically there are more molluscoids in the limestones.

Judging by the statements and lists of Girty, there are several features of the Kaibab fauna of Circle Cliffs, Utah, that mark it as definitely different from that of any Kaibab facies found in Arizona. The combination of numerous marine brachiopods, bryozoans, and sponges with a large molluscan assemblage is unknown elsewhere in the Kaibab. The brachiopods, although possibly including some species common to both areas, represent a very different group from that which characterizes the normal marine limestone of facies 1. The mollusks have not been identified closely enough either from this locality or from facies 3 and 4 to allow a critical comparison, but they include new species and genera, which suggests that they represent a distinctive facies, if not a different age. With present knowledge it is not possible to show an exact time equivalency between the type Kaibab fauna and that of Circle Cliffs, so the reference of the latter to the *β* mem-

²¹ G. H. Girty, in H. E. Gregory and R. C. Moore, *The Kaiparowits region*, U. S. Geol. Surv. Prof. Paper 164, pp. 42-43, 1931.

ber is necessarily tentative. Also, more detailed study may show that more than one member is represented.

In the San Rafael Swell, Utah, 65 miles north of Circle Cliffs, the writer made a small collection of fossils on the basis of which he has tentatively assigned the so-called Kaibab rocks of that area to the α and β members. These members, here as elsewhere, represent the time of receding sea and the time of most extended sea, respectively, but there is no proof that, as found in the San Rafael Swell, they correspond in time to the similar members in the type Kaibab area. The most abundant fossil in the β member of this area is *Spirifer pseudocameratus*, which is also common in the Kaibab near Fruita and Torrey on the Fremont River but which is unknown from any other part of the Kaibab formation. The next most common fossil is *Waagenoconcha montpelierensis*, which is likewise numerous in Circle Cliffs but is very scarce farther south in facies 1. In brief, though it also contains a brachiopod fauna, facies 5 shows no close faunal resemblance to the brachiopod limestones to the south and may not even be contemporaneous.

Boundary between α and β Members

In most of the Grand Canyon region and westward, the change from β to α members in the Kaibab formation is readily apparent because of the contrast between the crystalline, marine limestone of the former with its brachiopod fauna, and the thin-bedded, magnesian limestone of the latter with its molluscan fauna. East and south of this area, however, where the β member as well as the α member is represented by near-shore facies composed largely of impure, magnesian limestones and containing many of the common genera of Permian mollusks, the recognition of a boundary is more difficult.

Where the change from β to α member in the Kaibab formation is definite, any of three distinctive beds or horizons might be selected as the boundary. In nearly all Grand Canyon sections a thick bed of chert, in many places brilliant red or yellow in color, was the last deposit in the sequence formed under normal marine conditions. Above this lies another distinctive bed, a cross-bedded sandstone or sandy limestone which by the nature of its bedding and the frequent occurrence of trails in it heralds the departure of marine environment and the coming of brackish-water and continental deposits. Next above the cross-bedded deposit, in most places, appears the first of the thin-bedded, magnesian limestones with molluscan fauna, indicating that the boundary lies beneath it.

Were any of the three horizons referred to above persistent throughout the entire area of Kaibab deposition, an exact boundary could be easily assigned. As it is, inconsistencies arise in various sections making it necessary to place the boundary not in relation to any one marker bed but wherever the environment of most extended sea seems to be replaced by that of a receding sea as reflected in the rocks. In any case, such a stratigraphic

plane of separation is only approximately contemporaneous in different parts of the region. In a time of receding sea it marks successively later time, and consequently rises in the stratigraphic column, westward.

East of Grand Canyon along the Little Colorado Gorge and also south of Flagstaff on the Mogollon Plateau, two or more distinct beds of red and yellow chert are found at several localities. To complicate matters further, along the Little Colorado two or more cross-laminated beds are found, and these in places appear below and not above the chert beds. In such localities the combined chert beds and cross-bedded sandstones are probably best considered as a transition stage, and the base of the α member should be placed below the lowermost thin-bedded, magnesian limestone. The base of the series of limestones of this type should probably be considered the boundary between members at Grand Falls, Padre Canyon, and other eastern outcrops where the chert beds and cross-bedded sandstones are missing, although admittedly the contrast in lithology between the two members lessens in that direction, thus indicating more nearly uniform environmental conditions during the entire period of deposition.

α Member, Facies 1

As already noted, the α member of the Kaibab formation represents a time when the sea was receding from the region. It consists of deposits that are largely of residual types formed under shallow water and under continental conditions. Thin-bedded, magnesian limestones—some probably chemical precipitates, others containing “brackish water” fossils—red beds, gypsum deposits, and light-colored, cross-bedded sandstones are the principal lithologic types represented. This member has been variously termed in the literature the Bellerophon limestone, the Super Aubrey, the Harrisburg gypsiferous member, and the A member of the Kaibab limestone.

The α member of the Kaibab formation has been divided laterally into five facies, based partly on the dominant lithologic types represented in an area and partly on its fauna.

Facies 1, which occurs from Toroweap Valley westward, wherever erosion has not stripped it off the top of the formation, is characterized by a considerable thickness of red beds, gypsum deposits, and thin-bedded limestones. It is the portion of the member that Reeside and Bassler²² studied in northwestern Arizona and southwestern Utah and for which they proposed the name of “Harrisburg gypsiferous member.” Its fauna has not yet been studied in detail, but some of the limestones contain abundant mollusks of types common to other parts of the member, while certain other beds contain *Composita* and a few other brachiopods in great quantities (see plate 19).

²² J. B. Reeside Jr. and Harvey Bassler, *Stratigraphic sections in southwestern Utah and northwestern Arizona*, U. S. Geol. Surv. Prof. Paper 129, p. 58, 1922.

α Member, Facies 2

Facies 2 of the α member adjoins facies 1 to the east and includes, in general, the central portions of the member from a geographical standpoint. It is represented along the Grand Canyon in most sections from Hilltop

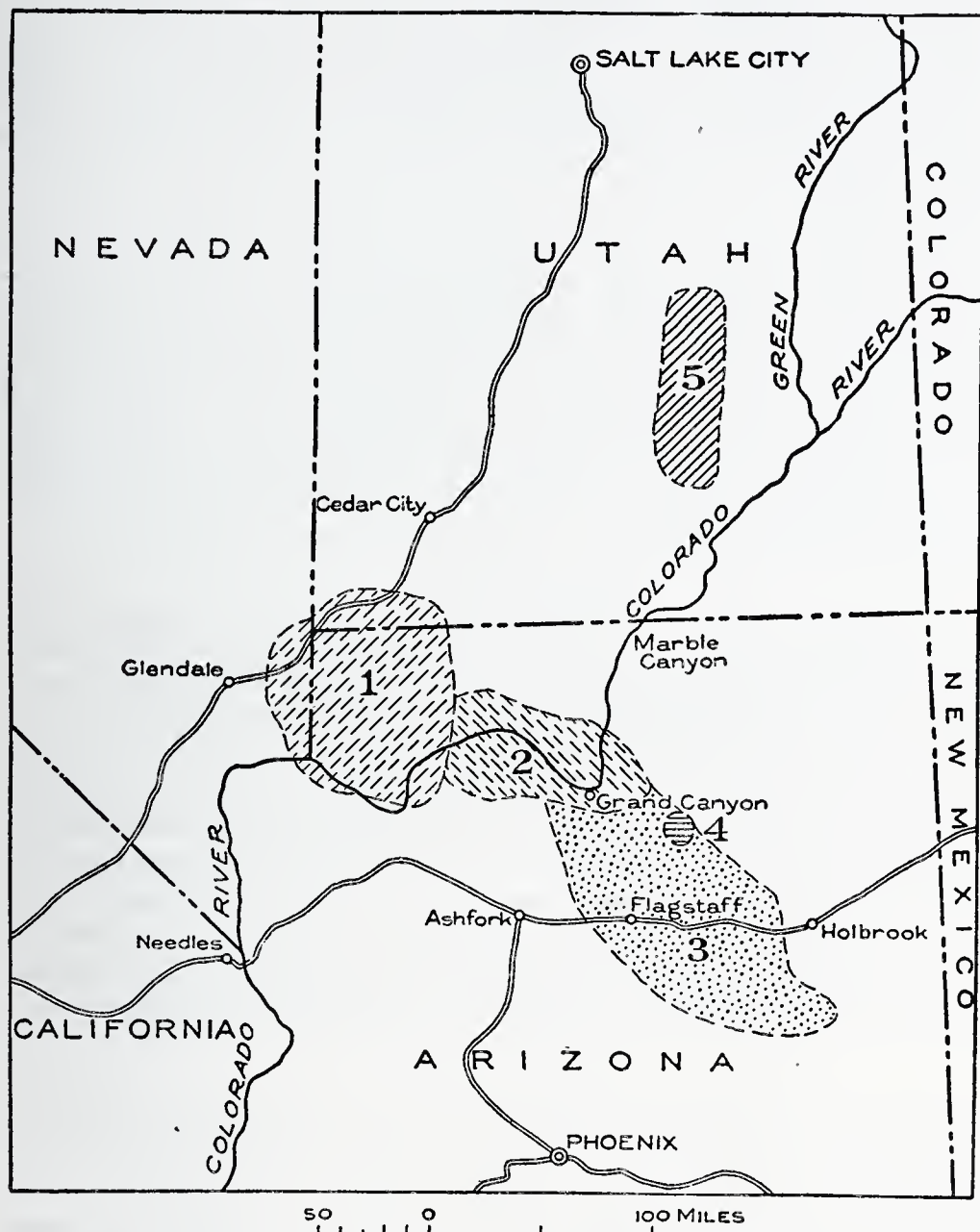


FIG. 23. Map showing distribution of facies comprising α member of Kaibab formation

(Havasü Canyon) to and along the Little Colorado. It differs from facies 1 largely in the absence of gypsum deposits and of brachiopod beds. At no place where it was examined, even where sections were complete to the Moenkopi contact, was it found to be nearly as thick as the facies to the west and south, but that may be due to pre-Triassic erosion.

The limestone of facies 2 consists of two principal types, each of which is distinctive in nature and easily recognizable. One of these characteristically weathers to a smooth surface and a blocklike structure. It is thin-bedded and barren of fossils, and in thin-section (plate 17*a*) shows a homogeneous, fine-grained character of the type attributed to chemical precipitates in chapter III. The other common form of limestone in the facies is also fine-grained (plate 17*b*) and thin-bedded, but in many places it contains abundant molds of mollusks and everywhere it weathers to a very rough pitted surface and a gray or brown color. The red beds of this facies are composed of crumbly, fine sand or silt and commonly show gnarly, irregular bedding.

The fauna of facies 2 of the α member is abundant and has long been well known so far as general character is concerned. It has been called the *Bellerophon* fauna in numerous places in the literature. In this assemblage are many species of pelecypods and gastropods, a scaphopod, a cephalopod, a trilobite, and locally a few brachiopods that appear to be holdovers from the open seas of the β member (plate 18). From a taxonomic standpoint these fossils are still very imperfectly understood, since the preservation of specimens is not favorable for close study. Most of them occur only as internal or external molds.

α Member, Facies 3

To the south and southeast of the Grand Canyon as far as the Kaibab formation is exposed, the α member is represented by thin-bedded, magnesian limestones of considerable aggregate thickness, except where recent erosion has partly or completely removed the beds. These limestones appear to be quite similar in general to those of facies 1 and 2, but contain none of the interbedded gypsum deposits or red beds, and constitute a considerably thicker series. As in facies 1 and 2, the limestones contain both the highly fossiliferous type which weathers with a rough, pitted surface, and the barren, uniform-textured type which weathers to smooth, even surfaces. Locally, cross-bedded white sandstones and layers of flat-bedded sandstone occur among the limestones and in one section some intraformational conglomerates were noted. This assemblage of beds is here designated as facies 3.

In many parts of facies 3 fossils are abundant, but they are poorly preserved, usually in the form of internal or external molds. Only limited collections of these fossils have been made as yet, so it is not now possible to give the exact status of the fauna. Pelecypods, scaphopods, and gastropods are the principal forms (plates 19 and 20), and these appear to differ little, if at all, from those of facies 2 which have been so extensively collected.

In the more easterly sections of the formation, facies 3 of the α member cannot always be easily distinguished from the underlying facies 4 of the β member, whose faunal assemblage shows the same general character. In

most places, however, the much greater massiveness of the lower beds and the sandy nature of most of these makes separation possible and logical.

α Member, Facies 4

Facies 4 of the α member is, so far as known, very local in distribution, but is characterized by a distinctive molluscan fauna. It is found in a limited area between Flagstaff and Cameron, Arizona, just north of the Rimey Jim Ranch a few miles east of the main highway between these places. The facies consists of limestone beds that weather to massive ledges with rough pitted surfaces. These are overlain by basal conglomerates and red beds of the Moenkopi formation.

Part of the distinctiveness of the facies 4 fauna—the exceptional nature of its preservation—is purely superficial. The fauna consists of a molluscan assemblage with many forms that are common to other parts of the formation, but the individual fossils, both on the surfaces and within the limestone matrix, have been completely silicified so that they may be readily etched out with acid. This palæontologist's paradise was discovered by Mr. L. F. Brady of the Museum of Northern Arizona in 1935, and many beautifully preserved fossils have subsequently been collected from it.

The true distinctiveness of the facies 4 fauna is found in its great preponderance of gastropod species, especially *Pleurotomaridæ*, and the comparative scarcity of pelecypod species. Only one species of brachiopod, *Productus bassi*, has been found, and this is not common. Scaphopods are numerous and a trilobite genus is represented (plate 21).

The abundant occurrence of the fossils in spherical pockets of limestone (plate 33*b*) and in limestone zones within larger units lithologically homogeneous, also the confinement of species to these areas, are features difficult to explain. The limestone within the fossil pockets is essentially the same as that outside, as indicated by a photomicrograph (plate 17*c*) showing a typical contact zone and the slightly sandy and porous, fine-grained limestone on each side. The boundaries of the fossil pockets appear to be less porous areas of limestone where a limonite crust gives a resistant character and a brown color. The writer cannot explain their significance.

α Member, Facies 5

For a distance of 70 miles northeastward from the exposures of unquestioned Kaibab formation in Marble Canyon, Arizona, strata of this formation are buried beneath a thick covering of Mesozoic rocks, hence it is not possible to correlate with certainty the members found in Marble Canyon with those of the so-called Kaibab limestone in Circle Cliffs or San Rafael Swell, Utah. Nevertheless, because the period of formation of the β member is defined as the time of most extended sea and the period of formation of the α member as that of receding sea, the strata in the Utah sections that represent these conditions are tentatively assigned to the respective members and are considered facies of them.

In the Circle Cliffs area of eastern Utah, provisional assignment of certain beds in the top part of the Kaibab formation to the α member is based on lithologic character alone, for no fossils have been collected from these beds. The rock is thin-bedded and composed of the same type of fine-grained, highly magnesian limestone which weathers to a rough pitted surface and forms so much of the α member in Arizona localities. In the various sections of the Circle Cliffs, these limestones, where found, contrast strongly with the more massive and more sandy underlying limestones which are assigned to the β member. In some of them occur intraformational conglomerates composed chiefly of angular chert fragments.

Sixty-five miles north of Circle Cliffs, Utah, the Kaibab formation appears in the San Rafael Swell. According to Gilluly, fossils from it "were determined by G. H. Girty to belong probably to the widespread *Bellerophon* zone, a relatively thin but persistent zone at the top of the Kaibab in the Grand Canyon district and adjacent regions to the north and west of it."²³ Examination of the Utah area by the writer in 1935 convinced him that such a correlation applies only to the uppermost beds of the formation in San Rafael Swell; that the lower portion, which contains a brachiopod fauna and is a combination of thicker-bedded, more sandy limestones and sandstones, is comparable with the β member, if with any unit, in the type Kaibab formation. The extent of the "*Bellerophon* zone" or α member in various sections of the San Rafael area is indicated by figure 23. Lithologically, as well as in general faunal composition, the strata assigned to this member resemble the thin-bedded, fine-grained, magnesian limestones with rough pitted surfaces which characterize all the facies of the α member found farther south.

UNCONFORMITY BETWEEN THE KAIBAB AND MOENKOPI FORMATIONS

That a persistent and significant unconformity of erosion exists throughout the Colorado Plateau area between the Kaibab formation of Permian age and the Moenkopi formation of Lower Triassic age has long been recognized by geologists working in this region. Exposures in which pre-Moenkopi erosion surfaces have been observed are scattered over a territory of more than 80,000 square miles.

Before the close of the nineteenth century, the writings of Gilbert,²⁴ Walcott,²⁵ and Dutton²⁶ had called attention to the fact that, at many places in southern Utah and northern Arizona, small erosion channels had been cut in the top of the Kaibab formation and filled with conglomerates of the overlying stratum. In more recent years at least twenty other geolo-

²³ James Gilluly and John B. Reeside Jr., *Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah*, U. S. Geol. Surv. Prof. Paper 150, p. 64, 1928.

²⁴ G. K. Gilbert, *Report on the geology of the Henry Mountains*, Rept. U. S. Geog. and Geol. Surveys Rocky Mtn. Region, p. 8, 1877.

²⁵ C. D. Walcott, *The Permian and other Paleozoic groups of the Kanab Valley, Arizona*, Amer. Jour. Sci., 3d ser., vol. 20, pp. 221-223, 1880.

²⁶ C. E. Dutton, *Tertiary history of the Grand Canyon district*, U. S. Geol. Surv. Mon. 2, p. 211, 1882.

gists have recorded evidence of various types and in various localities of the presence of the Kaibab-Moenkopi unconformity. No doubt the chief reason why so much consideration has been given this feature is that it involves the interval between the Paleozoic and the Mesozoic eras of geologic history.

The extent, nature, and significance of the Kaibab-Moenkopi unconformity has within recent years been discussed in detail by Dake,²⁷ Longwell,²⁸ Baker,²⁹ and others so that essentially all aspects of the problem have been given careful consideration. The writer is able to add very little to the knowledge that has already been obtained, and that small amount is largely in the form of additional detailed observations which merely substantiate well-established facts. It is desirable, however, to bring the principal recorded data and conclusions together in order to help complete a picture of the history of the Kaibab formation.

Region East and South of Grand Canyon

East and south of the Grand Canyon the Kaibab-Moenkopi contact is remarkably uniform in nearly all the many localities where it has been examined. Erosion of the upper limestone surface of the Kaibab formation has been noted in numerous places, but invariably the relief developed has been slight. Conglomeratic beds, containing mostly subangular, brightly colored chert pebbles of small size, form the base of the Moenkopi throughout this area except in the extreme eastern localities. Gregory³⁰ has described this unconformity from a number of places in the Painted Desert along the Little Colorado River, and the writer³¹ has given information concerning its occurrence and nature near the Grand Canyon and south of it.

Table 5 shows the character of the Kaibab-Moenkopi unconformity at a number of localities south and east of Grand Canyon where it has been recently examined by the writer. These data help to confirm the generalizations made earlier, but show three exceptions. First, although the Triassic basal conglomerates everywhere in the area contain only small, subangular pebbles, near Rimey Jim Ranch north of Flagstaff they include many very large, well-rounded limestone boulders (plate 22c). Second, in the three southeasternmost exposures examined, thin-bedded shales, and not conglomerates, occur at the base of the Moenkopi. Lastly, at one locality, near the Little Colorado Canyon, a slight discordance was noted between the strata of the two periods.

²⁷ C. L. Dake, *The pre-Moenkopi (pre-Permian?) unconformity of the Colorado Plateau*, Jour. Geol., vol. 28, pp. 61-74, 1920.

²⁸ C. R. Longwell, *The pre-Triassic unconformity in southern Nevada*, Amer. Jour. Sci., 5th ser., vol. 10, pp. 93-106, 1925.

²⁹ A. A. Baker and others, *Notes on the stratigraphy of the Moab region, Utah*, Bull. Amer. Assoc. Petrol. Geol., vol. 11, no. 8, pp. 785-808, 1927.

³⁰ H. E. Gregory, *Geology of the Navajo country*, U. S. Geol. Surv. Prof. Paper 93, p. 21, 1917.

³¹ Edwin D. McKee, *Occurrence of Triassic sediments on the rim of Grand Canyon*, Jour. Wash. Acad. Sci., vol. 25, no. 4, pp. 184-187, 1935.

TABLE 5. CHARACTER OF KAIBAB-MOENKOPI CONTACT SOUTH AND EAST OF GRAND CANYON

Locality	Nature of contact	Basal Moenkopi	Character of pebbles
Grand Canyon, near Hance Trail.....	Small erosion channels in limestone	Conglomerate, 4-16 ft. thick	Subangular quartz, chert, clay balls, max. size 1.5 in.
Little Colorado Canyon, N. of Cedar Mtn.....	Apparently even	Conglomerate, 4 ft. thick	Subangular, highly colored chert
Straight Canyon, N. of Cedar Mtn.....	Apparently even	Conglomerate, 3 ft. thick	Subangular quartz and chert in pink shaly matrix
Little Colorado Canyon, base of Waterloo Hill.....	Slight discordance	Red shale (in part), gray sandstone (in part), conglomerate above	None at base
Lee Canyon, SE. of Cedar Mtn.....	Not visible	Conglomerate, 3 ft. thick	Subangular chert, small
Base of Echo Cliffs, S. of Cedar Ridge.	Erosion channel in massive sandstone	Conglomerate (in part), green shale (in part)	Angular white chert
Near Badger Canyon, SW. of Lees Ferry.....	Small erosion channels in limestone and bedded chert	Conglomerate (in part), red shale (in part)	Angular white chert, coarse buff sandstone, av. size 2 in.
40 mi. N. of Flagstaff, Rimey Jim Ranch.....	Apparently even	Conglomerate, 15 ft. thick	Limestone boulders up to 3 ft. in diameter, rounded, upper part mostly small angular chert fragments
Grand Falls, Little Colorado.....	Apparently even	Conglomerate, 4 ft. thick	Angular chert and limestone pebbles in red, sandy matrix
Tolchico, Little Colorado.....	Apparently even	Conglomerate, 3 ft. thick	Limestone pebbles in red, silty matrix
Citadel Sink.....	Apparently even	Red, thin-bedded shale	No conglomerate
Meteor Crater, 0.5 mi. N.....	Apparently even	Yellow shale, 3 ft., sandstone above	No conglomerate
Winslow, 3 mi. SW..	Apparently even	Red, cross-bedded sandstone	No conglomerate
Winslow, 10 mi. SW. Sycamore Canyon...	Apparently even	Red shales	No conglomerate
	Erosion channel in limestone, 20 ft. deep	Limestone with pebbles, red shale above	
Long Valley 6 mi. NE.....	Uneven surface, channeled 2-3 ft.	Conglomerate	Angular and subangular, up to 4 in., cherts, quartz, clay balls, limestone

The isolated example of discordance between beds of the Kaibab formation and those of the Moenkopi is not surprising, and a similar example has been previously recorded from the Little Colorado Canyon area. In 1905 Ward stated that "about 4 miles above the limestone canyon there occurs a Paleozoic anticline as viewed from the bluffs, the limestone rising to a height of about 90 feet and again descending to the bed of the river, the length of the anticline being about 2 miles."³²

Southeastern Utah Region

In southeastern Utah there are three distinct and isolated areas where the Kaibab-Moenkopi contact is exposed. These are the San Rafael Swell, the Fremont River canyons, and the Circle Cliffs dome. Farther east in the Moab district, beyond the area of Kaibab deposition, a contact representing approximately the same time interval, i. e. between the Cutler and Moenkopi formations, is exposed.

Along the Black Box and various other canyons in the San Rafael Swell, evidence of unconformity between the Kaibab and Moenkopi formations is abundant. In many places small hollows eroded in the top of the Kaibab are filled with a gritty, white clay or with a conglomerate at the bottom of the Moenkopi. In some parts of the Swell the basal conglomerate is very persistent and at one place near the San Rafael River, where examined by the writer, it is 22 feet thick. It contains angular, white and bluish quartz and chert pebbles, with diameters commonly of 2 inches and exceptionally as large as 6 inches (plate 23c).

The Kaibab-Moenkopi unconformity not only is clearly visible locally, but also, as pointed out by Gilluly, "makes itself evident regionally by the disappearance and reappearance of the Kaibab limestone between the Cocalino sandstone and the Moenkopi formation."³³

South of the San Rafael Swell, along the Fremont River near Torrey and Fruita, sections of the Kaibab and Moenkopi formations have been examined by Dake.³⁴ Although an unconformity between these formations was not actually seen, evidence of its existence was furnished by difference in the horizon at the top of the Kaibab in adjoining sections.

In Circle Cliffs, Utah, evidence of a marked unconformity between the Moenkopi and the Kaibab formations has been noted both by Dake and by Gregory and Moore.³⁵ As in the Fremont River area, the extent of pre-Moenkopi erosion is indicated largely by a comparison of sections, showing

³² L. F. Ward, *Status of the Mesozoic floras of the United States*, U. S. Geol. Surv. Mon. 48, p. 38, 1905. The validity of Ward's observation is questioned by H. E. Gregory (personal communication, 1937), who has done considerable work along the Little Colorado River.

³³ James Gilluly, *Geology and oil and gas prospects of part of the San Rafael Swell, Utah*, U. S. Geol. Surv. Bull. 806, pp. 81-82, 1929.

³⁴ C. L. Dake, *The pre-Moenkopi (pre-Permian?) unconformity of the Colorado Plateau*, Jour. Geol., vol. 28, p. 67, 1920.

³⁵ H. E. Gregory and R. C. Moore, *The Kaiparowits region*, U. S. Geol. Surv. Prof. Paper 164, pp. 45-46, 1931.

the presence or absence of "marker" beds of both formations. This method undoubtedly gives fairly accurate results in the Circle Cliffs area, where distances between sections are not great and the "marker" beds are easily recognizable. Gregory and Moore have indicated that at least 40 feet and probably more of the Kaibab formation has been eroded away in parts of the area and that the amount removed increases toward the south and east. Dake concluded that the erosion amounted "in places to probably two hundred feet or more, with the complete removal at certain points, of the limestone beds, allowing the [Moenkopi] shales to rest directly on the [Utah "Coconino"] cross-bedded sandstone member."³⁶

Observations by the writer in the Circle Cliffs area substantiate those of Gregory and Moore which led them to state that there is no marked discordance in bedding nor any very noticeable irregularity of the upper surface of the Kaibab. Only in one locality, southwest of The Peaks, did the writer see any channeling in the Kaibab (plate 23a).

East of Circle Cliffs, the Kaibab formation is absent and erosion represented by the pre-Triassic unconformity is in the surface of the Cutler formation instead. From the vicinity of Moab, Utah, Baker³⁷ reports evidence of folding in addition to erosion which occurred at the close of the Permian. He states that in Moab Valley there is "an angular discordance of as much as 4 degrees, and the base of the Moenkopi rests in succession on strata from a horizon below the top of the Hermosa to a horizon in the Cutler 1000 feet above the top of the Hermosa."

In the foregoing review of recorded data describing the Permian-Triassic unconformity in southeastern Utah, certain marked similarities and differences are apparent as compared with conditions observed farther south in Arizona. Although in both areas evidence of discordance between the formations is exceptional and moderate erosion surfaces almost everywhere characterize the contact, in the Utah exposures erosion took place on a much greater scale. There, valleys were cut into the Kaibab to depths of 50 to 100 feet or more, while to the south the remarkably flat surface of the Kaibab seems only to have been channeled a few feet at most.

It has been suggested by Cross and by Dake, on the basis of studies made in the southeastern Utah area, that the pre-Moenkopi erosion surface transgresses downward stratigraphically toward the east. Longwell has pointed out that this theory was largely developed on incorrect correlations in the San Juan country and that there is no evidence to support it.

The Southern Nevada, Western Arizona, and Utah Area

In the region to the west and northwest of Grand Canyon, deep valleys were eroded into the Kaibab formation in many places during pre-Moenkopi time. "At the head of Rock Canyon" south of Hurricane, Utah, Reeside

³⁶ C. L. Dake, *The pre-Moenkopi (pre-Permian?) unconformity of the Colorado Plateau*, Jour. Geol., vol. 28, p. 65, 1920.

³⁷ A. A. Baker and others, *Notes on the stratigraphy of the Moab region, Utah*, Bull. Amer. Assoc. Petrol. Geol., vol. 11, no. 8, pp. 785, 796, 1927.

and Bassler found "a great gash 700 feet wide and 250 feet deep . . . cut into the Kaibab and filled with a confused mass of limestone, shale, gypsum and conglomerate."³⁸ Lee³⁹ records conglomeratic beds 125 feet thick resting unconformably on hard cherty Kaibab limestone and overlain by red shales near Cedar City to the north. In the Muddy Mountains farther west, according to Longwell, there are "local depressions or valleys 50 to 100 feet deep, cut into the Kaibab in early Triassic or pre-Triassic time [and] filled with chert and limestone fragments from the underlying rock."⁴⁰

In the westernmost known exposures of the Kaibab formation, in the Spring Mountains of Nevada, the greatest erosional discordance has been found. Glock noted that in the east central section of this range examples of erosion varied "from small valleys cut 75 feet into the Kaibab to [those involving] an entire removal of the Kaibab as well as much of the underlying Supai."⁴¹ Longwell⁴² states that some of these valleys were cut at least 1400 feet stratigraphically below the old surface east of Spring Mountain. In this area numerous other examples of pre-Moenkopi erosion surfaces exhibiting a considerable relief have been noted and described by Longwell.

Within the area of pronounced unconformity on the flanks of the Spring Mountains, Nevada, conglomerates everywhere lie at the base of the Moenkopi formation. These have been examined and described at length by Longwell.⁴³ He states that in coarseness, thickness, and detailed character they are extremely variable; that the pebbles and boulders are commonly angular or subangular with some as large as 2 feet or more in diameter; and that the fragments are mostly limestone and chert embedded in a limestone matrix. Longwell gives 65 feet as the greatest measured thickness of unbroken conglomerate and mentions solid beds of lime conglomerate 50 feet thick which can be traced half a mile or more. These features suggest pronounced local erosion but limited transportation of clastic materials.

Palæontologic Evidence of Unconformity

Evidence that the Kaibab-Moenkopi contact represents a hiatus of considerable magnitude—the time between the Middle Permian and Lower Triassic—is indicated by the fossils of the two formations, according to Shimer and to Girty.

³⁸ J. B. Reeside Jr. and Harvey Bassler, *Stratigraphic sections in southwestern Utah and northwestern Arizona*, U. S. Geol. Surv. Prof. Paper 129, p. 60, 1922.

³⁹ W. T. Lee, *The Iron County coal field, Utah*, U. S. Geol. Surv. Bull. 316, p. 362, 1907.

⁴⁰ C. R. Longwell, *Geology of the Muddy Mountains, Nevada, with a section to the Grand Wash Cliffs in western Arizona*, Amer. Jour. Sci., 5th ser., vol. 1, p. 49, 1921.

⁴¹ W. S. Glock, *Geology of the east-central part of the Spring Mountain Range, Nevada*, Amer. Jour. Sci., 5th ser., vol. 17, p. 333, 1929.

⁴² C. R. Longwell, *The pre-Triassic unconformity in southern Nevada*, Amer. Jour. Sci., 5th ser., vol. 10, p. 105, 1925.

⁴³ *Ibid.*, pp. 101-102.

Shimer states that "the conclusion is reached that the Kaibab with its 20 brachiopods, 7 pelecypods, and 2 gastropods, is of Permian age, while the Moenkopi with its 6 brachiopods, 21 pelecypods, and 11 gastropods, belongs probably to the Triassic period."⁴⁴ At another place he says that "an alternative to the lower Triassic age of the Moenkopi is that these sediments were deposited during the Upper Permian, and at this time there had evolved some forms which later became typical of the Triassic. In this paper, however, we incline to the belief that a period begins with the first distinct appearance of any portion of the fauna typical of it."

The Triassic age of the Moenkopi beds has been definitely established by Girty⁴⁵ on the basis of a specimen of *Meekoceras*—a distinctive ammonite of the Idaho faunas—and of a few other characteristic Triassic forms. He points out that there is an almost complete faunal change from the Kaibab to the Moenkopi and that the characteristic Paleozoic genera of brachiopods and bryozoa became extinct in this region following withdrawal of the Kaibab sea. From these facts, Girty concludes "that we have here an almost perfect example of a boundary between two geologic systems, the formations being separated by a profound erosional unconformity and by an almost complete change of fauna, the upper formation containing many diagnostic fossils of the later system and the lower formation containing many diagnostic fossils of the earlier system."

Conclusions

Many observations of the Kaibab-Moenkopi contact have been made throughout the region of its occurrence, hence it is now possible to formulate some generalizations and to draw certain conclusions with the assurance of a reasonable degree of accuracy. Longwell⁴⁶ has given an excellent analysis of this unconformity, which involves the interval between the Paleozoic and Mesozoic eras, in its broader aspects. His conclusions are summarized below and a few additional suggestions are contributed by the writer.

Field evidence indicates that, after the deposition of the Kaibab sediments, uplift occurred in the region. Six features of the movement appear to be definitely established:

1. The uplift was not uniform over the entire area. In the east and south, depressions and channels only a few feet in depth were worn in the Kaibab surface, and conglomerate beds at the base of the Moenkopi are everywhere thin. In the north and northeast, valleys were cut in many places to depths of 50 and 100 feet, and conglomerate beds are correspondingly thicker, while in the extreme northwestern part of the area, valleys

⁴⁴ H. W. Shimer, *Permo-Triassic of northwestern Arizona*, Bull. Geol. Soc. Amer., vol. 30, pp. 496-497, 1919.

⁴⁵ George Girty, in Reeside and Bassler, U. S. Geol. Surv. Prof. Paper 129, p. 68, 1922.

⁴⁶ C. R. Longwell, *The pre-Triassic unconformity in southern Nevada*, Amer. Jour. Sci., 5th ser., vol. 10, pp. 93-106, 1925.

as deep as 1400 feet and conglomerate deposits 65 feet thick suggest pronounced local upwarping.

2. The uplift was not very great over the region as a whole. At no place were extensive deposits beveled off the surface. This is shown by the fact that the uppermost member of the Kaibab formation is still represented in every part of the region. Erosion took the form of channeling and valley cutting and, except in the Spring Mountain area of Nevada, even this produced no great results.

3. The uplift was not of long duration. The elevated areas were only partially reduced by erosion, and the general stripping-off of entire members did not occur in any part of the region, indicating that time was not sufficient for the development of a mature topography.

4. An arid climate prevailed during the uplift. The fact that gypsum deposits near the top of the Kaibab formation remained through this period indicates aridity, and the character and amount of erosion suggest the same thing, although the latter feature involves also the factors of time and the amount of elevation.

5. That the submergence which permitted the invasion of the Lower Triassic sea and the deposition of Moenkopi sediments was rapid, appears certain. It is indicated by the preservation of a hill and valley topography, by the lack of marine planation from west to east, by the general flatness of the surface, which would allow rapid ingress of the sea, and by the limestone at the base of the Moenkopi in the western area. Also sand, mud, and other elastic sediments are common in the basal conglomerate as found in the east, but are rare in western exposures.

6. The time represented by the unconformity was sufficiently long to allow complete consolidation of the sediments represented in the Triassic conglomerates. As indicated by fossils, it spanned the interval between the Middle Permian and the Lower Triassic, which is the duration of the Upper Permian.

III. SEDIMENTARY TYPES IN THE TOROWEAP AND KAIBAB FORMATIONS

LIMESTONES

Character and Distribution

The Toroweap and Kaibab formations as defined in this paper contain such a large proportion of limestone that together they were formerly referred to as the Aubrey limestone, later as the Kaibab limestone. Despite the fact that recent detailed examination has shown that these formations also include an abundance of other types of sediments, the importance of the limestone units is not to be denied, nor should the diversity of types of limestone be overlooked.

In the Toroweap formation the entire middle member of the western phase is limestone, which extends as a great wedge thinning from west to east. Sections in Nevada show that there it is several hundred feet thick, light gray, crystalline, and massive. Farther east the limestone becomes less pure and weathers usually with a buff or brownish color. The magnesium content increases and clastic sediments become more abundant as the thickness diminishes. The fauna changes completely to types characteristic of brackish waters.¹ Finally along a north-south line just east of the Kaibab Plateau, past Desert View and between Seligman and Sycamore Canyon, this limestone unit disappears.

Other limestone beds are present in the α member of the Toroweap formation, associated with the red beds and gypsum deposits of facies 1. These limestones are all thin-bedded, in many places banded, and everywhere highly magnesian in character. With one exception they are barren of fossils. Such beds, also, normally form a transition stage between the red beds both above and below the β member, and the massive limestone of that member.

In the Kaibab formation gray, crystalline limestone, relatively pure but containing much concretionary chert, forms the massive cliffs of the β member in facies 1. It extends from Nevada eastward to a point near Hermit Trail in Grand Canyon with a thickness of several hundred feet throughout. Farther east, in facies 2, this limestone becomes increasingly sandy and much finer-grained, and is interbedded with layers of chert. To the south and east, in facies 4, the member is also composed of limestone. It is fine-grained but relatively free from clastic sediments, is high in magnesium, and contains a specialized fauna typifying brackish or highly saline waters.

The α member of the Kaibab formation contains limestone of two general types, both of them thin-bedded and formed under lagoonal conditions.

¹ It is possible that this environment was one of greater salinity than normal rather than less, but the evidence at hand (see chapter IV) favors the latter hypothesis.

One of these types is a mouse-gray limestone of fine, uniform texture, containing no fossil remains and weathering to small blocks with smooth surface and sharp corners. This type will be discussed under "Chemically Precipitated Limestones." The second type is a fine-grained, gray limestone which weathers with extremely rough, pitted, brown or gray surfaces and contains the molds of mollusks in abundance. This will be discussed under "Magnesian Limestones." Both of these types are present over a wide area and are interbedded with gypsum and red beds in facies 1 and with red beds alone in facies 2. Elsewhere they jointly have considerable thickness but are unattended by other types of sediments except for a few zones of horizontally bedded sandstone.

Normal Marine Limestones

In both the Toroweap and Kaibab formations, the middle or β member represents a time when the sea reached a maximum advance. In each instance the limestone in the western portion of the member bears evidence of having been deposited under normal conditions of a shallow, quiet, but open sea. Most of this limestone is coarsely crystalline, pure, and of homogeneous character. It weathers into thick, massive ledges and cliffs. In the Kaibab, a fauna consisting of many species of brachiopods and bryozoans, of crinoids, horn corals, sponges, and pelecypods of the pecten type is abundantly represented throughout. The first three of these animal groups are also common in the Toroweap formation. Clastic sand grains are scarce and the magnesium content is low; silica in the form of chert concretions, often developed around sponges, is scattered throughout the Kaibab beds and occurs locally in the Toroweap.

During the time of deposition of Toroweap sediments, normal marine waters advanced eastward only a little farther than the present Toroweap Valley. Farther east the limestone which formed in that sea shows a steady increase in amount of clastic sand. Even more notable changes, however, are found in the decrease in grain size, the increase in magnesium content, and the complete replacement of the molluscoids by mollusks.

In the Kaibab formation normal marine conditions prevailed eastward as far as the present Hermit Trail in Grand Canyon. Shoreward from there the crystalline limestone merges into sandy limestone and calcareous sandstone, and the character of the fauna changes as in the case of the Toroweap. Marked changes in texture and magnesium content are likewise apparent in this direction.

The general character of the Permian limestones of the Colorado Plateau, which are here described as typical of the open-sea areas, has been observed in thin-sections. In the eastern or near-shore portions, where fine clastic grains appear through the limestone, subangular quartz forms probably 98 per cent of the sand grains. Fragments of feldspar, tourmaline, rutile, and mica are rare, and other minerals are seldom noted. Iron oxides are commonly present but are not conspicuous. These clastic constituents

are essentially absent to the west (in both formations) and thin-sections show coarsely granular limestone, in places containing fossil outlines. In some places the skeletons of organisms constitute the bulk of the rock.

Chemical analyses bring out other features of the Toroweap and Kaibab limestones. The following analysis of a "hard, gray, crystalline, somewhat cherty limestone" from the β member of the Kaibab formation, Bass Trail, is given by Noble:²

Insoluble	11.15 per cent
(Al,Fe) ₂ O ₃	0.71
CaO	48.68
MgO	0.00

He states that "probably the insoluble impurities are largely the silica that forms nodules of chert," for no detrital sand was present. This analysis illustrates the high lime content and the lack of magnesium which appears to be typical of the coarsely crystalline limestones. Analyses 1, 2, and 3 in table 6, made by Professor F. H. Fish from samples of this crystalline limestone collected by the writer at Fossil Mountain, substantiate these conclusions. Number 4, from the same locality but lower in the member, is high in silica because of elastic quartz but it shows also a lack of magnesium.

TABLE 6. CHEMICAL ANALYSES OF LIMESTONE FROM KAIBAB FORMATION, β MEMBER *

	Fossil Mountain, uppermost gray crystalline limestone	Fossil Mountain, base of massive gray crystalline limestone	Fossil Mountain, massive gray crystalline limestone above 2	Fossil Mountain, gray sandy limestone near base	Hermit Trail, lowest <i>Productus</i> zone	Hermit Trail, upper <i>Chonetes</i> zone	Hermit Trail, <i>Murchella Composita</i> zone	Yaki Trail, upper massive limestone	Yaki Trail, sandy limestone between chert beds
	%	%	%	%	%	%	%	%	%
Loss on ignition....	36.59	40.85	25.49	9.75	19.69	36.73	40.72	34.14	2.75
SiO ₂	14.14	7.61	40.62	77.00	54.05	17.98	13.11	24.59	93.03
R ₂ O ₃	0.08	0.27	0.91	1.07	1.84	2.62	1.71	2.29	0.73
CaO.....	47.35	50.15	31.05	11.90	25.45	29.45	27.52	23.05	2.97
MgO.....	1.19	....	....	....	....	15.93	18.00	17.05	0.72
Total.....	99.35	98.88	98.07	99.72	100.38	99.71	101.06	101.12	100.20

* Analyses through courtesy of Professor F. H. Fish, Department of Chemistry, Virginia Polytechnic Institute.

A comparison of the analyses of crystalline limestones from Fossil Mountain with those of the stratigraphically similar but finer-grained limestones from farther east at Hermit and Yaki Trails is illuminating. The fine-grained samples from near-shore deposits show a high percentage of

² L. F. Noble, *A section of the Paleozoic formations of the Grand Canyon at the Bass Trail*, U. S. Geol. Surv. Prof. Paper 131, p. 69, 1922.

MgO except in sample 9, where clastic sand grains are so numerous that the lime and magnesium contents are necessarily very low. In the Toroweap formation samples from near-shore facies of the β member illustrate a similar high percentage of MgO, as shown by analysis in table 8. Unfortunately no analyses of the coarse-grained limestone from the open-sea facies of the Toroweap formation are available for comparison.

TABLE 7. CHEMICAL ANALYSES OF LIMESTONES FROM KAIBAB FORMATION, α MEMBER *

	Hermit Trail, "Bellerephon" limestone at base	Yaki Trail, "Bellerephon" limestone at base
	%	%
Loss on ignition.....	45.01	45.29
SiO ₂	3.94	2.72
R ₂ O ₃	1.49	0.67
CaO.....	29.32	31.25
MgO.....	20.78	21.66
Total.....	100.54	101.59

* Analyses through courtesy of Professor F. H. Fish, Department of Chemistry Virginia Polytechnic Institute.

TABLE 7a. BOTH PROBABLY FROM α MEMBER, KAIBAB FORMATION *

	Upper part of formation, canyon SE. of Flagstaff, near mouth of sewer	Upper part of formation, vicinity of Elden Mountain
	%	%
SiO ₂	72.21	20.56
Al ₂ O ₃	1.82	2.70
Fe ₂ O ₃	1.04	
MgCO ₃	5.62	
CaCO ₃	18.60	23.96
		52.90
Total.....	99.34	100.02

* Analyses by F. N. Gould. From Robinson, U. S. Geol. Surv. Prof. Paper 76, 1913.

Table 7 gives analyses of limestones from the α member of the Kaibab formation. Because these limestones are relatively thin-bedded, contain specialized fossils of brackish or highly saline waters, and are associated with red beds, it is believed that they were formed under nearly landlocked conditions. The analyses show these limestones to have a higher magnesium content than any others examined, and thus they stand in strong contrast with the coarse-grained limestones of the normal marine environment.

The coarse-grained character of much of the typical marine limestone in the Toroweap and Kaibab formations is a feature of interest and importance in the interpretation of these rocks. Such coarse granularity of limestone has been variously explained, according to Swartzlow,³ as the result of (1) geologic age, (2) influence of accessory constituents, (3) rate of precipitation, and (4) environment of deposition.

³ Carl R. Swartzlow, *Dolomitization and origin of granularity in Chouteau limestone*, Pan Amer. Geologist, vol. 59, no. 4, p. 277, 1933.

TABLE 8. CHEMICAL ANALYSES OF LIMESTONES FROM TOROWEAP FORMATION, β MEMBER *

	Fossil Mountain, thin-bedded limestone above base	Fossil Mountain, main massive limestone cliff	Fossil Mountain, top thin-bedded limestone	Hermit Trail, top of main cliff	Hermit Trail, thin-bedded brittle limestone	Hermit Trail, lowermost limestone bed	Hermit Trail, middle of main cliff	Yaki Trail, base of main cliff	Yaki Trail, middle of cliff	Yaki Trail, top of main cliff
Loss on ignition...	% 36.85	% 39.90	% 45.28	% 41.44	% 42.46	% 41.18	% 38.21	% 37.78	% 27.64	% 42.84
SiO ₂	19.89	12.63	1.27	10.58	8.66	9.38	14.80	18.58	37.42	7.64
R ₂ O ₃	1.65	0.75	0.47	0.93	0.01	1.92	3.21	1.22	1.34	1.12
CaO.....	28.00	28.13	31.33	27.85	28.06	28.85	26.95	24.88	19.14	28.40
MgO.....	13.99	17.37	21.06	19.16	18.73	18.49	18.00	17.32	13.68	19.90
Total.....	100.58	98.78	99.41	99.96	99.92	99.82	101.17	99.78	99.22	99.90

* Analyses through courtesy of Professor F. H. Fish, Department of Chemistry, Virginia Polytechnic Institute.

That geologic age (implying depth of burial, hence pressure) is not the determining factor in explaining the coarse-grained character of the marine limestones in the Toroweap and Kaibab formations is apparent, because the members that include marine beds also contain very fine-grained limestone in near-shore facies. Furthermore, in underlying, older limestones throughout the area, both coarser- and finer-grained types are present.

TABLE 9. CHEMICAL ANALYSES OF LIMESTONES FROM TOROWEAP FORMATION, α MEMBER *

	Fossil Mountain, "pelecypod" limestone	Hermit Trail, "pelecypod" limestone
Loss on ignition.....	% 44.38	% 38.78
SiO ₂	3.15	14.13
R ₂ O ₃	1.17	1.39
CaO.....	30.98	29.49
MgO.....	19.85	16.13
Total.....	99.53	99.92

* Analyses through courtesy of Professor F. H. Fish, Department of Chemistry, Virginia Polytechnic Institute.

That the presence of accessory constituents has been important in the development of the coarse granularity in the Permian marine limestones of Arizona and Utah is also doubtful. Analyses and thin-sections indicate that these limestones are relatively very pure and that both magnesium and argillaceous materials are nearly lacking, although these substances are abundant in many of the fine-grained, near-shore facies of the same limestone members. As suggested by Swartzlow,⁴ probably the real significance

⁴ *Ibid.*, p. 279.

of the lack of mud is that its absence indicates very quiet conditions of deposition. The lack of magnesium—a substance which is usually precipitated rapidly when concentration and conditions for precipitation are reached and which normally is present in fine-grained aggregates—suggests that the rate of precipitation may have been slow; however, it is no proof of this.

Rate of deposition and environment appear to have been the significant factors responsible for the coarse-grained texture of these limestones. The distance from shore, the abundance of well-preserved organic remains, and the almost complete absence of clastic materials and of features such as cross-lamination and ripple marks, indicate that these beds were formed at the bottom of a quiet, shallow sea which no doubt was warm, judging from the numerous corals and echinoids present. Here, the surface layers of the sea were presumably saturated with calcium carbonate which was gradually precipitated as a result of the action of one or more of the agencies that are known to cause loss of carbon dioxide in the water.

Thus a slow accumulation of calcite crystals allowed growth of large grains, while probably contemporaneous recrystallization, as suggested by the anhedral character, developed the grain size even more and caused the rock to become compact.

Regarding the origin of the normal marine limestones of the Toroweap and Kaibab formations, it seems probable that most if not all are related to the activities of organisms. Such activities may form limestones or assist in forming limestones in various ways. It is a well-established fact that actual accumulations of limy skeletons form some limestones, and plate 13a illustrates a sample from the Kaibab formation in Toroweap Valley which appears to have been formed largely in this manner. Plate 13c illustrates a sample from the same formation farther east, or near the shore. It shows no evidence of organisms, but is coarsely crystalline in character and contains a large number of clastic quartz grains.

An organic process that produces CaCO_3 and that may easily account for much of the coarsely granular limestone in the formations just referred to has been stated by Steinmann: "Albumen, which is present in the organic parts of all animals, is a distinct precipitating agent. By fermentation the albuminoids generate ammonium carbonate, and to that compound the precipitation of calcium carbonate is due."⁵ The abundance of skeletons found in the marine facies of the Arizona Permian formations lends much support to this theory of limestone origin.

Still another possible factor in producing the Kaibab and Toroweap marine limestones, but one for which no evidence either direct or indirect has been found, is the work of algæ. According to Clarke, "in the shallow seas which are thought to have covered a large part of the North American continent the calcium carbonate may well have been thrown down by algæ,"⁶ but he states that for a permanent deposit the water must have

⁵ G. Steinmann, *Ber. Naturforsch. Gesell. Freiburg*, vol. 4, p. 288, 1889.

⁶ F. W. Clarke, *The data of geochemistry*, U. S. Geol. Surv. Bull. 695, p. 549, 1920.

been warm and shallow. Bacteria, likewise, might have been important in the limestone formation. Studies of the activities of these organisms and of the part supposedly played by them in the precipitation of CaCO_3 , particularly as found on the Bahama Banks, have been made by Drew. It should be added, however, that several later students of the subject have concluded that the bacteria were only incidental to the process, and, since no evidence along this line is furnished by the Permian limestones in question, the subject need not be discussed here.

In addition to the organic processes mentioned, it is also conceivable that mere alteration of water conditions, brought about by changes in temperature or in concentration of carbon dioxide, might have been responsible for laying down these limestones. This does not appear likely, however, because of the extent and uniformity of the deposits, the location in the midst of an open sea, and the evidence of associated lime-secreting organisms. Further discussion of this inorganic type of limestone and its criteria is given in the section entitled "Chemically Precipitated Limestones."

The following tabular classification, from Twenhofel,⁷ giving modes of limestone origin, reviews the possible types, most of which might apply to the Toroweap and Kaibab marine limestones.

- A. Limestones directly or indirectly resulting from organic processes:
 - 1. Accumulation and cementation of protective and supporting structures of organisms
 - 2. Limestones developed through the vital activities of organisms:
 - a. Photosynthesis of plants
 - b. Bacterial precipitation
 - 3. Limestones developed through decay of organic matter
- B. Limestones of chemically inorganic origin:
 - 1. Changes of conditions in water containing calcium carbonate in solution
 - 2. Evaporation
- C. Limestones of mechanical origin

Sandy Limestones

Many limestone beds in both the Toroweap and Kaibab formations contain detrital sand grains in greater or less proportion; however, in this discussion only the sandy limestones that make up a major portion of facies 2 in the β member of the Kaibab are referred to. These particular beds are sufficiently extensive and characteristic, it is thought, to justify mention as a distinctive type of limestone.

The general character of the sandy limestones of the Kaibab formation may be readily seen by reference to the photomicrograph of a typical specimen (see plate 13c). The grain of the limestone is in general much finer than that in corresponding beds farther west. The amount of clastic sand

⁷ W. H. Twenhofel, *Treatise on sedimentation* (Baltimore: Williams & Wilkins Co.), p. 216, 1926.

varies widely with the sample and in some instances is sufficiently great to form a sandstone. All but a negligible quantity of this detrital matter is quartz. The rock itself, as seen in the field, usually forms massive ledges separated by bedded cherts which, being less resistant to erosion, commonly undermine the limestones. The latter normally weather to fairly rough surfaces with gray or buff color.

The significance of the sandy limestones of the Kaibab is apparent from a consideration of their lateral distribution and relationships in the field. They occur through a narrow strip which extends north-south, or parallel to the ancient shore line, as indicated on the map (figure 22). To the west they merge gradually into the pure crystalline limestones of the open seas, already discussed, and eastward they grade into pure, fine-grained sandstones containing a fauna totally different from that in the limestones to the west. In brief, the sandy limestones of the β member of the Kaibab may be regarded as a transition between the near-shore sandstones and the open-sea, coarse-grained limestones, and they happen to have been deposited in the same general area and alternating with beds of chert.

Chemically Precipitated Limestones

The process of forming limestone by chemical precipitation has been described and discussed by numerous geologists. Johnston and Williamson⁸ have shown that calcium carbonate is deposited from sea water by a rise in temperature or a drop in the concentration of atmospheric carbon dioxide, the surface layers of the ocean being usually saturated with respect to the carbonate. This type of deposition can take place only in very shallow waters, because in a deep sea the precipitate forming on the surface will redissolve before settling to the bottom. Factors that may assist in such chemical precipitation of CaCO_3 in shallow, lime-saturated bodies of water are influxes of fresh waters charged with carbonates and the entire or near absence of lime-consuming organisms, as explained by Clarke.⁹

The characteristics of chemically precipitated limestones have been summarized by Daly,¹⁰ who has given considerable study to this type of deposit, especially in its relation to the pre-Cambrian seas. He states: "The constituent particles are either idiomorphic and roughly rhombohedral, or anhedral and faintly interlocking. The former are everywhere of nearly uniform average diameter, ranging from .01 millimeter to .03 millimeter, with an average of about .02 millimeter. The anhedral grains range from .005 millimeter to .03 millimeter, averaging about .015 millimeter in diameter."

Confirmation of his figures given for grain size of chemically precipitated limestones is found by Daly in the calcareous mud of the Black Sea,

⁸ J. Johnston and E. D. Williamson, *The rôle of inorganic agencies in the deposition of calcium carbonate*, Jour. Geol., vol. 24, p. 729, 1916.

⁹ F. W. Clarke, *The data of geochemistry*, U. S. Geol. Surv. Bull. 695, p. 547, 1920.

¹⁰ R. A. Daly, *First calcareous fossils and the evolution of the limestones*, Bull. Geol. Soc. Amer., vol. 20, pp. 153-170, 1909.

known to be of such origin, and in the average diameters of calcite and dolomite crystals of undoubted chemical precipitation in sea water or saline solution at ordinary temperatures. Furthermore, calcite granules, 0.02 to 0.03 millimeter in diameter, were found to have been deposited from sea water in cavities of Funafuti corals.

Uniformity of grain is believed to be a second criterion of chemically precipitated limestones. This is the case in such modern deposits as those of the Black Sea and the delta of the Rhone. Strata thought to be of this type in the Rocky Mountain geosyncline are described by Daly, who says, "Neither horizon nor distance from the old shorelines affects the singularly monotonous grain of the rocks."

Both the Kaibab and the Toroweap formations contain a distinctive type of limestone which the writer believes to be a chemical precipitate. Wherever found, it may be easily recognized, for it is different from other limestones of the area both in surface characteristics and under the microscope. Everywhere thin-bedded, its usual thickness is 2 or 3 inches and few beds exceed one foot. Weathering develops smooth, angular blocks. The usual color is a pale mouse gray on both fresh and weathered surfaces.

In thin-section, the chemically precipitated limestones of the Kaibab and Toroweap formations show a very uniform, homogeneous, fine-grained texture which might be termed "monotonous" (plate 17a). Individual grains in the sections examined ranged between 0.01 and 0.02 millimeter in diameter and were euhedral or subhedral. No traces of fossils have been noted in the limestone and clastic sand grains have been found extremely scarce in the specimens studied. In a typical sample from the α member of the Kaibab, for instance, only one staurolite, one magnetite, one iron oxide, and twelve quartz grains were noted in thin-section.

Chemically precipitated limestones, associated with the gypsum deposits of the Toroweap formation, frequently show a fine horizontal banding. Similar banding of limestone in the Castile anhydrite of Texas has been illustrated and referred to by Lang,¹¹ who states that the laminae consist of calcium carbonate with the darker ones more heavily impregnated with carbonaceous material. The bands he believes are varves, probably representing annual deposits. Such a theory may also apply to the banded limestones of the Toroweap, but sufficient detailed study of these has not been made to justify any conclusions.

The general distribution and the type of associated sediments of the chemically precipitated limestones of both the Toroweap and the Kaibab formations are important evidence of the origin that has been postulated for them. These limestones are consistently found in horizons where they might logically be expected to occur, and only in such horizons. Among the red beds and especially near the gypsum deposits in both formations they are numerous, appearing at scattered horizons and localities, isolated

¹¹ W. B. Lang, *Upper Permian formation of Delaware Basin of Texas and New Mexico*, Bull. Amer. Assoc. Petrol. Geol., vol. 19, no. 2, p. 268, 1935.

among these other deposits. In the Toroweap formation, this type of limestone almost always is present also as a transition stage between the red beds of the basal member and the fossiliferous, marine limestones above (β member); likewise it is found at the top of the fossiliferous limestone, where it forms a transition into the overlying red beds of the α member.

Still another feature noted in some of the chemical limestones which gives evidence of their origin is the presence of shrinkage cracks on the surfaces. A typical example from near the base of Toroweap α in Parashant Canyon, Shivwits Plateau, is illustrated in plate 6a. Regarding such sun cracks in limestone, Barrell concludes "that the seas of those particular epochs were essentially marine playas, extremely shallow pans of sea waters. These were repeatedly emptied, not by the rapidly recurrent ebb and flow of tides, but possibly by monsoon winds or at longer intervals by extremely slight changes in the relative elevation of the playa bottom with respect to the sea level."¹² Evaporation appears to be an even more likely cause for the loss of water covering in the case of the Permian deposits here considered.

In summary, the writer wishes to point out that the thin-bedded, pale gray limestones which weather to smooth, angular blocks, found in both the Kaibab and Toroweap formations, are probably due to chemical precipitation because: (1) they have a uniform, fine texture comparable to that in modern chemically precipitated limestones; (2) they are usually associated with gypsum deposits or are present as a transition stage between red beds and fossiliferous marine limestones; (3) they give no evidence of the presence of any type of organism; (4) some are finely laminated and usually they are free from clastic sand, thus indicating quiet conditions of deposition; (5) they are comparatively local in distribution and are found at varying horizons.

Dolomitic Limestones: β Member of Kaibab Formation

Tracing the massive limestone member (β) of the Kaibab formation eastward or toward the ancient shore line from the contemporary open sea, the beds become not only increasingly sandy but also more highly magnesian and finer-grained. Examples of these magnesian beds are found both in facies 2 of eastern Grand Canyon, where limestone beds alternate with those of chert, and in facies 4, which extends south from the Little Colorado over most of the Mogollon Plateau. In facies 2, clastic sand constitutes such a large proportion of the chert-free beds that its matrix of dolomitic limestone is relatively unimportant, hence these beds are discussed under the heading of sandy limestone. In facies 4, however, the dolomitic limestone contains a much smaller proportion of sand and is interbedded with relatively pure limestone.

Chemical analyses of dolomitic limestones from the Kaibab formation

¹² J. Barrell, *The criteria for the recognition of ancient delta deposits*, Bull. Geol. Soc. Amer., vol. 23, p. 443, 1912.

are listed in table 6. Thin-sections show characteristic dolomite rhombs in fine-grained limestone. The number generally is not great. Typical dolomitic limestones of this type alternate with pure limestone on the sides of Walnut Canyon. Describing these, Shimer states that "the limestones usually consist almost entirely of small marine fossil fragments, and leave after solution in acid a very small residue of quartz grains; the dolomites, usually granular, and with few or no fossils, contain a varying amount of quartz grains, probably averaging 30%–50% of many of the beds."¹³ He also observed that the more porous strata are dolomitic, while the purer, less porous ones are not.

Because the origin of dolomites is a highly controversial subject, it is thought desirable to review briefly the various theories that have been advanced and to show what field and petrographic evidence from the Kaibab formation either supports or opposes each. The following principal modes of origin will be discussed:

- I. Syngenetic origin due to
 - a. Changes in temperature and concentration of atmospheric CO₂
 - b. Production of ammonium carbonate during decomposition of the remains of marine organisms
 - c. Decomposition of shells or skeletons containing carbonates
 - d. Mechanical deposition
- II. Epigenetic origin, after consolidation, due to
 - a. Replacement
 - b. Concentration resulting from leaching of more soluble calcium salt
- III. Epigenetic origin, before consolidation or uplift, due to
 - a. Concentration resulting from leaching of more soluble calcium salt
 - b. Replacement

Concerning the various methods of forming dolomites before consolidation of the sediments, Clarke states that "all four processes may go on at the same time with one or another predominating according to conditions."¹⁴

Deposition of dolomite by chemical precipitation has been considered by many geologists. Regarded as evidence of such an origin is the "existence of fine-grained, structureless dolomites apparently devoid of organisms," especially where formed in restricted seas under conditions of concentration, as stated by Skeats.¹⁵ He concluded that such deposits, while known in nature, are restricted to landlocked areas of the type that develop salt and gypsum deposits. Furthermore, Clarke¹⁶ has suggested that deposits precipitated by ammonium carbonate from the decay of marine organisms must likewise be limited in extent, since the process of decomposition also develops CO₂, which tends to retain carbonates in solution.

¹³ H. W. Shimer and F. H. Shimer, *The lithologic section of Walnut Canyon, Arizona, with relation to the cliff-dwellings of this and other regions of northwestern Arizona*, Amer. Anthropologist, vol. 12, p. 248, 1910.

¹⁴ F. W. Clarke, *The data of geochemistry*, U. S. Geol. Surv. Bull. 695, p. 570, 1920.

¹⁵ E. W. Skeats, *The formation of dolomite and its bearing on the coral reef problem*, Amer. Jour. Sci., 4th ser., vol. 45, no. 267, pp. 188–189, 1918.

¹⁶ F. W. Clarke, *The data of geochemistry*, U. S. Geol. Surv. Bull. 695, p. 570, 1920.

Experiments have demonstrated that dolomite can be formed by chemical precipitation. Hunt¹⁷ has shown that heat is an important factor, while Pfaff¹⁸ and others have demonstrated the importance of pressure. Pfaff concluded that conditions comparable to those of his experiments might exist in concentration of sea water. Van Tuyl¹⁹ attempted to produce dolomite as a direct chemical precipitate by evaporating for a month solutions of the bicarbonates of calcium and magnesium in molecularly equivalent proportions, but obtained only separate precipitates, first of CaCO_3 and later of MgCO_3 . He concluded, therefore, that chemically precipitated dolomite deposits would have to be formed "under conditions which doubtfully operate in nature, at least on a large scale."

Other types of syngenetic dolomite deposits may be disregarded, at least so far as the Kaibab dolomitic limestones are concerned. For obvious reasons, mechanical deposition could not apply to these beds. The scarcity of fossils and the composition of their shells, furthermore, precludes the possibility of origin through partial solution of the skeletons of organisms.

The restriction of the Kaibab dolomitic limestones to the near-shore facies suggests that the magnesium was a constituent of the original marine waters. It is inconsistent with the theory of dolomitization after consolidation of the sediments and uplift. Certain other features of these sediments, however, give evidence that the dolomite was not an original precipitate, but was developed later than the associated materials. Typical thin-sections from Clear Creek Canyon (Mack's Crossing) show dolomite rhombs concentrated around pores or openings but rarely within dense portions. More striking still, thin-sections of bedded cherts, nodular cherts, and sandy limestones from facies 2 at Grand Canyon illustrate instances of dolomite replacing silica in clastic grains.

In considering the epigenetic origin of dolomite it is important to distinguish between the nearly contemporaneous types and the subsequent ones which are developed long after the formation of the limestone, usually after it has been elevated above sea level. Evidence that the latter type is not represented by the dolomitic limestones of the Kaibab formation is abundant. First, the restriction of the dolomite to areas where near-shore environments prevailed and only brackish-water faunas occurred is too consistent a feature to be the result of mere coincidence. Second, the dolomite shows no relationship to fissures, joints, or other entrance channels. Third, no logical source for the magnesium is found, either in overlying dolomites or in magmatic materials.

Differential leaching of slightly magnesian limestones by carbonated waters, thus increasing the percentage of magnesium, is a hypothesis which has been advanced to explain epigenetic dolomites. This process might

¹⁷ T. S. Hunt, *Amer. Jour. Sci.*, 2d ser., vol. 28, pp. 170-365, 1859; vol. 42, p. 49, 1866.

¹⁸ F. W. Pfaff, *Centralbl. Min., Geol. und Pal.*, p. 659, 1903.

¹⁹ F. M. Van Tuyl, *New points on the origin of dolomite*, *Amer. Jour. Sci.*, 4th ser., vol. 42, pp. 252-253, 1916.

take place either in the sea, prior to emergence, or by ground waters after the limestone has become a part of the land. In either case, however, the restriction to near-shore facies of the formation with molluscan faunas, and the interbedding with pure limestones, make the application of this theory to the Kaibab deposits untenable. Furthermore, Skeats has shown that in a normal fresh limestone "long before the rock is completely dolomitized, it must be reduced to a quite structureless mass, and all traces of organisms must necessarily disappear."²⁰ Such is not the case in the dolomitic limestones of the Kaibab.

In the study of the Kaibab dolomitic limestones, it has been shown that field and petrographic evidence make untenable each of the various theories of dolomite origin that have been discussed. By the process of elimination, therefore, only the theory of metasomatic replacement appears to explain satisfactorily the various features noted. The distribution of the deposits, the concentration of dolomite rhombs near pores, and the evidence of dolomite forming later than silica, all support the thesis that dolomitization was a secondary process that took place on the sea floor before consolidation of the sediments. As pointed out by Skeats, in this type of deposit since "the sea is the only possible source of magnesium, it follows that the dolomitization of the limestone followed so closely on its formation as to be almost contemporaneous with it in a geological sense."²¹

Numerous students have stressed the point that dolomites are formed only in very shallow waters. That such was the case with the Kaibab dolomites is suggested not only by their distribution in the formation, but also by the abundance of associated clastic sand grains and by the character of the contained fauna. The paucity of the latter, moreover, lends further support to this view, for it probably indicates the unfavorable environment which would naturally be caused by a high salinity of the water.

The amount of time available for replacement and the degree of permeability in limestones have been suggested as factors which retard or facilitate dolomitization in shallow waters. The importance of permeability seems to be indicated in a section like that in Walnut Canyon, where dense limestones and porous dolomites are interbedded. The porosity may be, in part, a secondary feature due to reduction of volume during dolomitization, but the larger cavities obviously cannot be explained in this manner.

Dolomitic Limestones: β Member of Toroweap Formation

In both the Toroweap and Kaibab formations the massive, cliff-forming β or middle members represent times of maximum extension of the sea. In both cases marine faunas are found in the westernmost facies, while brackish-water assemblages replace them to the east. With this the similarity ends.

²⁰ E. W. Skeats, *The formation of dolomite and its bearing on the coral reef problem*, Amer. Jour. Sci., 4th ser., vol. 45, no. 267, p. 192, 1918.

²¹ *Ibid.*

In the β member of the Kaibab formation there is a transition eastward from coarse-grained, pure limestone into sandy dolomitic limestone and bedded chert, then to fine sandstone, all without appreciable change in total thickness of the beds. In contrast with this, the β member of the Toroweap formation is a wedge which tapers toward the east, and, although it becomes gradually more sandy in that direction, it shows no transition into sandstone nor does it contain a bedded chert facies.

In the Toroweap formation the outstanding characteristics of the limestone in the eastern or near-shore portions (facies 2) of the β member are its dense, fine-grained character, its high magnesium content, and the abundant but poorly preserved molluscan fauna which it contains. Clastic sand grains are not uncommon, especially toward the east. Its general appearance in thin-section is shown in plate 9b and its magnesium content by the chemical analyses in table 8.

The term dolomitic limestone rather than dolomite is applied to the rocks that make up the facies described above since they effervesce freely upon application of cold acid, yet show numerous dolomite rhombs in thin-sections. The amount of evidence at hand does not justify any definite conclusions concerning the origin of this dolomite. It is apparent, nevertheless, that the beds were laid down in the near-shore portions of the sea and that they grade into the open-sea deposits of the formation as is the case with those of the Kaibab dolomitic limestones. It is clear, also, that they were not formed in landlocked pools or embayments. From this it appears probable that, like the Kaibab dolomitic limestones, they were developed by partial replacement of limestone by dolomite while the calcareous deposits were still unconsolidated on the sea floor.

Dolomitic Limestones: α Member of Kaibab Formation

Throughout the α member of the Kaibab formation are certain limestones that are distinctive because of extremely rough pitted surfaces, relatively thin beds, high magnesium content, usually abundant but poorly preserved molluscan fossils, and general absence of clastic sand grains. In color these limestones range from pure gray to tan, but both fresh and weathered surfaces of an individual bed usually show the same color. These limestones will be referred to hereafter as the dolomitic limestones of the Kaibab α member, and they should not be confused with the more massive dolomitic limestones of the β member, previously discussed.

In the α member of the Kaibab formation dolomitic limestones of the type just described are found in every facies. South and east of Grand Canyon in facies 3 they alternate with beds of other thin-bedded limestones, thought to be chemical precipitates, and in some places with flat-bedded sandstones. In this area the total thickness of such "lagoonal" deposits (α member) is locally 100 feet or more. To the north along eastern Grand Canyon the dolomitic limestones are associated with red beds and

also with chemically precipitated limestones, but usually they form only a small rim above the massive cliff-forming sediments of the β member. Farther west, in facies 1, similar limestones form a minor part of the so-called Harrisburg gypsiferous member, with red beds and gypsum making up most of its thickness. Everywhere the individual beds of this limestone have a thickness of 1 or 2 feet; nowhere are they massive and cliff-forming as are most of the underlying beds of the β member.

The dolomitic limestones of the α member, Kaibab formation, effervesce readily in cold acid, yet have a high magnesium content, as indicated by chemical analyses, tables 7 and 7a, which show over 20 per cent MgO in each sample, an amount greater than that found in any other limestone of the Kaibab formation. This fact is consistent with the theory, based on field evidence, that these limestones were formed on the bottoms of very shallow, nearly landlocked basins left by the retreat of the sea, whereas the massive dolomitic limestones present in lower members were formed in marginal portions of the open seas, where sedimentary barriers were less effective and normal conditions less modified.

The almost complete lack of clastic sand grains in most of the α member dolomitic limestones suggests that they were deposited in quiet water. A typical sample from Yaki Point in Grand Canyon effervesced freely and continuously in cold acid until it practically disappeared in a few days, leaving as a residue only 0.2 per cent of the sample in the form of fine sand grains. On the other hand, in a few places along the Little Colorado Canyon and farther east certain beds contain a sprinkling of quartz grains, so dispersed through the limestone as to suggest that they might have been blown or rafted into the water.

Fossils are extremely abundant in the α member dolomitic limestones, and doubtless were responsible for the forming of the limestone. Almost everywhere the fossils are preserved only as internal or external molds, and many are fragmentary, hence specific identification is difficult. Gastropods, especially of the *Bellerophon* type, pelecypods, and scaphopods are most numerous, and trilobites are not uncommon. Brachiopods and bryozoans are scarce and usually dwarfed, while crinoids, corals, and sponges are absent.

The faunal assemblage found in the α member dolomitic limestones of the Kaibab formation is of the type to be expected in shallow basins where the waters are either brackish or highly saline. It is of interest to note, however, that in waters containing as much magnesium as did the Kaibab, forms of life were not of those types that Clarke²² has shown (see table 10) to have a considerable amount of magnesium in their shells, but rather of those groups that use virtually pure CaCO_3 . Possibly the explanation for such an apparent contradiction of facts is that, in the open seas, the abundant fauna of crinoids, bryozoans, and brachiopods used up most of the

²² F. W. Clarke and W. C. Wheeler, *The inorganic constituents of marine invertebrates*, U. S. Geol. Surv. Prof. Paper 124, 1922.

TABLE 10. THE CHEMICAL COMPOSITION OF SOME MARINE INVERTEBRATE SKELETONS *

Name	CaCO ₃	MgCO ₃	SiO ₂	Representation in Kaibab α member
	%	%	%	
Crinoids.....	83-92	8-14	T-6	Rare or absent in magnesian limestone
Bryozoa.....	63-97	1-11	T-17	
Calc. brachiopods.....	89-99	T-9	T-1	
Pelecypods.....	99-100	0-1	T	Present in magnesian limestone
Gastropods.....	97-100	0-2	T	
Cephalopods.....	94-100	0-6	T	
Scaphopods.....	98-99	T	T-1	

* After Clarke. All figures condensed to nearest whole number.

available magnesium, hence the granular limestone deposited by other means is relatively free from this substance. In shallow brackish or highly saline pools near shore, on the other hand, because the fauna consisted entirely of forms that did not use magnesium in their shells and because conditions favored its concentration, the magnesium was abundantly deposited.

CHERTS AND RELATED SILICEOUS DEPOSITS

Theories of Origin

Any attempt to interpret the history of the marine portions of the Kaibab formation in terms of sedimentation, ecology, or palæogeography would be futile without a careful consideration of the types of chert and related siliceous deposits that constitute such a large percentage of the entire rock mass. So conspicuous and abundant are the chert deposits throughout much of the formation that practically every writer who has described or discussed it has referred to this feature. In every place where the massive cliffs of the β member are found, from eastern Grand Canyon north and westward into Utah and Nevada, chert beds or layers of chert concretions and nodules are interlaminated with and included in the beds of calcareous sandstone or limestone.

The origin of chert has been discussed by many geologists working in many regions. Numerous have been the theories and the resulting controversies regarding this question, yet it is impossible to avoid the subject if a true understanding of a formation such as the Kaibab is to be obtained. A convenient summary of the principal theories that have been advanced has been given by Barton.²³ Of these theories, three suggest organic and three inorganic sources. Classified another way, three of them refer to deposition prior to consolidation of the enclosing sediments and three to deposition at a subsequent date.

The consideration of a landscape, environment, or ecologic condition of the past is directly concerned only with those chert deposits that were

²³ D. C. Barton, *Notes on the Mississippian chert of the St. Louis area*, Jour. Geol., vol. 26, pp. 361-374, 1918.

formed before consolidation of the formation. The theories which would have affected this history, therefore, are those that suggest an origin due (1) to colloidal silica derived from decomposition of siliceous sponges and other siliceous organisms collected in depressions on the sea floor, (2) to immediate replacement of parts of limestone (before consolidation) by silica derived from solution of scattered siliceous spicules, and (3) to direct precipitation of dissolved silica from sea water.

Although not pertinent to the depositional history, it is nevertheless very important that cherts deposited in the formation at a subsequent date be recognized as such. Otherwise the interpretation of the physical features controlling its history would be unsound. The principal theories of secondary origin are: (1) the replacement of consolidated limestone by silica dissolved by percolating waters from siliceous spicules, (2) the precipitation of silica and replacement of limestone in the presence of circulating waters that have passed through sandstone, or rocks containing silica or silicates, and (3) the diffusion of silica in solution through limestone with concentration varying in direction of diffusion and deposition resulting when concentration is sufficient.

Criteria Used by Others as Evidence of Origin of Chert

Before describing and discussing the various types of chert in the Kaibab formation, it is advisable to consider the principal features that have been observed and used by other students of chert as criteria supporting the various theories of origin which they have advanced or adopted. Since most of the physical features that have been referred to as evidence of one origin or another are represented in one or more of the Kaibab chert types, this summary of interpretations is entirely pertinent. It should be realized, however, that in numerous cases features may be interpreted in more than one way, and thus may fail actually to contribute any proof to a theory as contended by the sponsor.

Shape. The shapes of concretionary chert deposits have been cited as evidence of several contrasting theories of origin. According to Tarr,²⁴ globular and spherical forms are due to the tendency of colloids to aggregate in masses, whereas ellipsoidal or lenticular forms result from the compression of sediments; thus, both forms are most readily explained by the colloidal precipitation theory. Some others,²⁵ on the other hand, hold that the ellipsoidal or lenticular shape assumed by many nodules is due to greater growth on the sides where water entered along bedding planes, and they regard such forms as evidence of secondary action. Sollas²⁶ suggested that nodular shape indicates zones where growth of sponges was unusually profuse. Other opinions on this subject have been expressed by

²⁴ W. A. Tarr, *Origin of the chert in the Burlington limestone*, Amer. Jour. Sci., 4th ser., vol. 44, p. 421, 1917.

²⁵ W. A. Tarr, *The origin of chert and flint*, Univ. Missouri Studies, vol. 1, no. 2, p. 37, 1926.

²⁶ W. J. Sollas, *Age of the earth* (London: T. F. Unwin), p. 154, 1905.

Van Tuyl,²⁷ who points out that the very irregular shapes of some nodules suggest replacement, and by Smith,²⁸ who states that presence of chert in numerous nodules and short lenses is opposed to a theory of chemical precipitation.

Concerning the origin of bedded cherts there apparently is little controversy. In discussing deposits of this type, Davis²⁹ says that rhythmic bedding is best explained by colloidal segregation, Mansfield³⁰ notes that the presence of chert in broad sheets at definite horizons is favorable to the theory of chemical precipitation, and Taliaferro³¹ contends that widespread, rhythmically banded cherts cannot be explained as secondary.

Distribution. A second aspect of chert deposits that has been subject to considerable discussion is their regional and local distribution. Where they are found principally along fissures, bedding planes, stylolites, or other partings, development subsequent to recrystallization has been postulated. This type of evidence has been used by Van Tuyl,³² Fowler and Lyden,³³ and Giles.³⁴ In contrast, the distribution of chert within massive beds and not along bedding planes is suggested by Tarr³⁵ and by Smith³⁶ as evidence of primary instead of secondary origin of chert. Van Tuyl³⁷ agrees that such distribution argues against replacement after consolidation of the matrix, but postulates replacement on the sea bottom soon after deposition.

The universal distribution of chert in planes or zones parallel to bedding planes of the enclosing rock is thought by Tarr³⁸ to be indicative of primary origin. Van Tuyl,³⁹ Fowler and Lyden,⁴⁰ and Giles,⁴¹ on the other hand, point to a lack of distribution along or within any given plane as one of their reasons for postulating a secondary origin. Smith⁴² states that widespread, erratic distribution is opposed to both the secondary and chemical precipitation theories of origin.

²⁷ F. M. Van Tuyl, *The origin of chert*, Amer. Jour. Sci., 4th ser., vol. 45, p. 450, 1918.

²⁸ W. S. T. Smith, in Fowler, Lyden, Gregory, and Agar, *Chertification in the Tri-State Mining District*, Amer. Inst. Mining and Met. Eng., Tech. Pub. No. 532, p. 55, 1934.

²⁹ E. F. Davis, *The radiolarian cherts of the Franciscan group*, Univ. Calif. Pub., Bull. Dept. Geol., vol. 2, no. 3, pp. 402-408, 1918.

³⁰ G. R. Mansfield, *Geography, geology and mineral resources of southeastern Idaho*, U. S. Geol. Surv. Prof. Paper 152, pp. 367-370, 1927.

³¹ N. L. Taliaferro, *The relation of volcanism to diatomaceous and associated siliceous sediments*, Univ. Calif. Pub., Bull. Dept. Geol. Sci., vol. 23, no. 1, pp. 1-56, 1933.

³² F. M. Van Tuyl, *op. cit.*, pp. 450, 456.

³³ Fowler and Lyden, *op. cit.*, p. 16.

³⁴ A. W. Giles, in Fowler, Lyden, Gregory, and Agar, *op. cit.*, p. 54.

³⁵ W. A. Tarr, *The origin of chert and flint*, Univ. Missouri Studies, vol. 1, no. 2, pp. 16, 37, 1926.

³⁶ W. S. T. Smith, *op. cit.*, p. 55.

³⁷ F. M. Van Tuyl, *op. cit.*, p. 456.

³⁸ W. A. Tarr, *op. cit.*, p. 16.

³⁹ F. M. Van Tuyl, *op. cit.*, p. 450.

⁴⁰ Fowler and Lyden, *op. cit.*, p. 31.

⁴¹ A. W. Giles, *op. cit.*, p. 54.

⁴² W. S. T. Smith, *op. cit.*, p. 55.

Other features of distribution, considered by various writers to have significance, are as follows: Constant association with calcareous rock, rather than indiscriminate association with limestone, sandstone, and shale, is suggested by Smith⁴³ as evidence against chemical precipitation. Concentration in areas of deformation or disturbance is considered by Fowler and Lyden⁴⁴ and by Giles⁴⁵ as proof of secondary origin, and the former also point out that some chert horizons seen on cliff faces are unrepresented a short distance in—further evidence of secondary development. Giles⁴⁶ refers to upward decrease in chertification as suggestive of a magmatic origin, while Leith⁴⁷ suggests a relationship between the widespread development of cherty materials and old erosion surfaces. According to Tarr,⁴⁸ further evidence of primary origin is found in laminations that wrap around chert nodules but do not pass through them.

Composition and Texture. The interpretation of the transitional surface layer on many concretions and nodules has given rise to disagreement among students of chert. According to Gregory⁴⁹ and also Fowler and Lyden,⁵⁰ the mixed material intermediate between chert and limestone, commonly called "cotton rock,"⁵¹ is due to incomplete replacement; on the other hand, this feature is explained by Tarr⁵² as a result of leaching. The latter further suggests, as does Smith,⁵³ that a sharp contact indicates an abrupt stop in precipitation of silica. Smith⁵⁴ considers that "cotton rock" may be explained either way. Giles⁵⁵ states that the variable composition of chert indicates a secondary origin, but Clarke⁵⁶ believes that the intermediate gradations shown by analyses indicate that the chert and the limestone were deposited together in the same ooze. Calcareous lenses in bedded chert are thought by Tarr⁵⁷ to be a normal feature of primary deposition, and gradual transitions from chert to limestone are regarded as evidence of replacement by several writers.⁵⁸

Advocates⁵⁹ of the secondary origin of chert have frequently pointed to the presence of limestone fragments within a matrix of chert as evi-

⁴³ *Ibid.*

⁴⁴ Fowler and Lyden, *op. cit.*, pp. 26, 31.

⁴⁵ A. W. Giles, *op. cit.*, p. 54.

⁴⁶ *Ibid.*

⁴⁷ C. K. Leith, *Silicification of erosion surfaces*, Econ. Geol., vol. 20, pp. 513-523, 1925.

⁴⁸ W. A. Tarr, *op. cit.*, p. 35.

⁴⁹ F. E. Gregory, in Fowler, Lyden, Gregory, and Agar, *op. cit.*, p. 36.

⁵⁰ Fowler and Lyden, *op. cit.*, p. 28.

⁵¹ Defined by Fowler and Lyden as a rock intermediate between chert and limestone.

⁵² W. A. Tarr, *op. cit.*, pp. 16, 34, 38.

⁵³ W. S. T. Smith, *op. cit.*, p. 55.

⁵⁴ *Ibid.*, p. 57.

⁵⁵ A. W. Giles, *op. cit.*, p. 54.

⁵⁶ F. W. Clarke, *The data of geochemistry*, U. S. Geol. Surv. Bull. 695, p. 543, 1920.

⁵⁷ W. A. Tarr, *op. cit.*, p. 38.

⁵⁸ F. E. Gregory, p. 43, W. M. Agar, p. 48, A. W. Giles, p. 54, in Fowler, Lyden, Gregory, and Agar, *op. cit.*

⁵⁹ F. E. Gregory, *op. cit.*, pp. 41, 43; F. M. Van Tuyl, *op. cit.*, p. 450.

dence of replacement, but Tarr⁶⁰ maintains that this is the result of limestone being enclosed by nodules growing around it. Lindgren describes a place where "ragged calcite grains lie embedded in this (chert) mass, giving evidence of metasomatic origin of the chert by replacement of calcite by siliceous waters."⁶¹ Sellards⁶² thinks flint masses that seem to "conform to no rule as to size and extent" in limestone suggest secondary development.

A feature of some cherts that apparently has value as a criterion of origin is the preservation of original structures and textures, especially the relics of bedding, as pointed out by Van Tuyl⁶³ and Giles,⁶⁴ although the latter cites the freedom of chert from sea-floor sediment as evidence against primary origin. Regarding inherited structures as evidence of replacement, Tarr⁶⁵ and Smith⁶⁶ argue that the general lack of mimicking of any parent rock by cherts indicates that most of them are primary. Tarr⁶⁷ also states that chert of one color and limestone of another is evidence against secondary development.

Banding in cherts is thought to indicate, in general, a secondary origin. Tarr⁶⁸ believes that the absence of banding in most examples shows chert to be largely of primary origin. Gregory⁶⁹ states that bands are the result of invading silicic acid solutions following horizons of highest solubility. Opposed to this supposition are the results of experiments by Davis⁷⁰ in which he produced artificially alternate layers of fine clay and clear silica gel that appeared as fairly regular, rhythmic bands, thickening, thinning, and terminating as lenses. According to Tarr⁷¹ the colored bands in many nodules are shown to be original by their widening and narrowing.

A feature of composition that has been considered an indicator of origin is the appearance in thin-section of small circular areas of amorphous silica. These were interpreted by Hill and Jukes-Browne⁷² as due to breaking up of sponge spicules, but Tarr⁷³ believes that they indicate original areas of colloidal silica, since they contain nothing to indicate organic origin.

⁶⁰ W. A. Tarr, *op. cit.*, p. 38.

⁶¹ W. Lindgren, *The copper deposits of the Clifton-Morenci district, Arizona*, U. S. Geol. Surv. Prof. Paper 43, pp. 62-66, 1905.

⁶² E. H. Sellards, First Ann. Rept. Florida Geol. Surv., p. 49, 1908.

⁶³ F. M. Van Tuyl, *op. cit.*, p. 450.

⁶⁴ A. W. Giles, *op. cit.*, p. 54.

⁶⁵ W. A. Tarr, *Origin of the chert in the Burlington limestone*, Amer. Jour. Sci., 4th ser., vol. 44, p. 448, 1917.

⁶⁶ W. S. T. Smith, *op. cit.*, p. 55.

⁶⁷ W. A. Tarr, *The origin of chert and flint*, Univ. Missouri Studies, vol. 1, no. 2, p. 35, 1926.

⁶⁸ *Ibid.*

⁶⁹ F. E. Gregory, *op. cit.*, p. 39.

⁷⁰ E. F. Davis, *op. cit.*, p. 400.

⁷¹ W. A. Tarr, *op. cit.*, p. 6.

⁷² W. Hill and A. J. Jukes-Browne, *Colloidal silica in the lower chalk of Berks and Wilts*, Quart. Jour. Geol. Soc., vol. 45, p. 40, 1889; *idem*, Geol. Mag., vol. 6, p. 237, 1889.

⁷³ W. A. Tarr, *op. cit.*, p. 10.

Fossils. Fossils that are present in or associated with many chert deposits have been given careful consideration in this connection by practically every student of chert, and in many cases they have been found to suggest a mode of origin. In this summary fossils will be discussed in the following sequence: (1) siliceous types, (2) unreplaced calcareous types, (3) replaced calcareous types, (4) casts of calcareous types, (5) comparison between types within and without chert masses, and (6) special varieties of fossils.

Advocates of the organic origin of chert usually contend, where fossils are lacking, that siliceous skeletons have been dissolved and redeposited. Julien ⁷⁴ states that the presence of sponge structure indicates the influence of decaying matter in bringing about the solution of silica. Sollas ⁷⁵ says that nodules containing sponge spicules suggest the possibility of partial solution and reprecipitation around a sponge nucleus, and Hinde ⁷⁶ also considers sponges to be the source of silica in nodules. The prevailing excess of silica about sponge centers led Prestwich ⁷⁷ to consider them simply as nuclei to which colloiddally dispersed silica was attracted, and Twenhofel ⁷⁸ suggested that they were nuclei of replacement.

Evidence against the organic origin of cherts is of two principal types. The general lack or inadequate supply of sponge spicules, diatom tests, or other siliceous organisms in most cherts makes it difficult to attribute to them the extraction of the silica from normal sea water. This point has been made by Davis,⁷⁹ Mansfield,⁸⁰ Taliaferro,⁸¹ and others. Tarr ⁸² points out that in Hinde's discovery of "one hundred and sixty forms of sponges" in one chert nodule, he has evidence that the nodule served as a source of silica for the sponges and not the sponges for the nodule. A second type of evidence of non-organic origin is found in the excellent preservation and entire lack of solution of the spicules and other siliceous parts. This argues against the theory that many of the spicules were partially dissolved and the silica redeposited. It has been referred to by Renard,⁸³ Tarr,⁸⁴ and Taliaferro.⁸⁵ The last also points out that he finds no evidence of secondary silicification of either foraminifera or glass shards.

Calcareous fossils found inside of chert masses or adhering to the surfaces are cited by Tarr ⁸⁶ as evidence of primary silica deposition. When

⁷⁴ A. A. Julien, *Proc. Amer. Assoc. Adv. Sci.*, vol. 28, p. 396, 1880.

⁷⁵ W. J. Sollas, *Ann. and Mag. Nat. Hist.*, 5th ser., vol. 6, pp. 384, 387, 1880; vol. 7, p. 141, 1881.

⁷⁶ G. H. Hinde, *Philos. Trans.*, vol. 176, p. 403, 1885; *Geol. Mag.*, vol. 4, p. 435, 1887; vol. 5, p. 241, 1888.

⁷⁷ Joseph Prestwich, *Geology, chemical, physical, and stratigraphical* (Oxford: Clarendon Press), vol. 2, pp. 320-324, 1886-1888.

⁷⁸ W. H. Twenhofel, *Amer. Jour. Sci.*, 4th ser., vol. 47, pp. 407-429, 1919.

⁷⁹ E. F. Davis, *op. cit.*, pp. 402-408.

⁸⁰ G. R. Mansfield, *op. cit.*, pp. 367-370.

⁸¹ N. L. Taliaferro, *op. cit.*, pp. 1-56.

⁸² W. A. Tarr, *op. cit.*, p. 41.

⁸³ A. F. Renard, *Bull. Acad. Roy. Belgique*, ser. 2, vol. 46, pp. 471-498, 1878.

⁸⁴ W. A. Tarr, *op. cit.*, p. 10.

⁸⁵ N. L. Taliaferro, *op. cit.*, pp. 1-56.

⁸⁶ W. A. Tarr, *op. cit.*, p. 14.

similar species in the surrounding limestone are found in silicified form this seems especially probable.

Replaced calcareous fossils in certain cherts indicate secondary origin of these cherts according to Van Tuyl.⁸⁷ Furthermore, he believes that the association of silicified fossils and chert in the same limestone shows a similar origin. This, however, is indirect evidence. Tarr⁸⁸ points out that where calcareous fossils have been replaced through the action of ground water, slow deposition gives rise to a distinctive fibrous chalcedony or quartz.

It has been noted by several writers that, where the fossil forms of lime-secreting animals are present as casts or molds in chert, perfect preservation of shell configuration is the rule. Van Tuyl⁸⁹ attributes this feature to partial replacement, but several other writers⁹⁰ have interpreted it as indicating that an animal has been entombed in a gelatinous mass and later dissolved away. Added weight is given to this theory by examples where fossils in the surrounding limestone do not show the same good preservation.

The following types of evidence involving fossils have also been suggested as indicating primary origin of the associated chert: structures showing the activity of algæ and bacteria in forming the chert;⁹¹ worm borings in nodules, indicating that the latter must have been soft when the worms were present;⁹² approximately equal distribution of fossils outside chert and in, suggesting that the original number is still represented;⁹³ minute fossils well preserved in chert cavities, indicating rapid deposition.⁹⁴

Factors limiting age. In numerous examples the time of chert formation can be definitely limited by related factors. Tarr⁹⁵ has referred to areas of folding in which chert lenses and beds are involved, thus indicating that the silica was deposited before the deformation. Several writers⁹⁶ have noted pebbles of a particular chert type in conglomerate beds of known age higher in the section, and Fowler, Lyden, and Gregory⁹⁷ discuss in detail the presence of fragments of one type of chert in another of later age. Obviously in this case the younger chert, at least, is of secondary origin.

Lack of evidence of subsequent growth on fresh or weathered specimens of chert, also examples of faulted nodules in which there is perfect healing,

⁸⁷ F. M. Van Tuyl, *op. cit.*, p. 450.

⁸⁸ W. A. Tarr, *op. cit.*, pp. 11, 14, 39.

⁸⁹ F. M. Van Tuyl, *op. cit.*, pp. 449-456.

⁹⁰ W. A. Tarr, *op. cit.*, pp. 7, 14, 39; G. R. Mansfield, *op. cit.*, pp. 367-370; W. S. T. Smith, *op. cit.*, p. 57.

⁹¹ J. W. Gruner, *The origin of sedimentary iron formations*, Econ. Geol., vol. 17, pp. 407-460, 1922.

⁹² W. A. Tarr, *op. cit.*, p. 19.

⁹³ *Ibid.*, p. 10.

⁹⁴ *Ibid.*, p. 6.

⁹⁵ *Ibid.*, p. 17.

⁹⁶ *Ibid.*; Fowler and Lyden, *op. cit.*, pp. 12-13; F. E. Gregory, *op. cit.*, p. 36.

⁹⁷ Fowler and Lyden, Gregory, *op. cit.*, pp. 7, 37.

without quartz or chalcedony cementation, are believed by Tarr⁹⁸ to be criteria of primary origin. Smith⁹⁹ suggests that cherts must precede stylolite development, since the stylolites do not cut through but follow the limestone-chert contact. Certain preconsolidation features such as shrinkage cracks in nodules, some filled with limestone of the type in the matrix, are occasionally found. These can be explained only as primary, according to Tarr¹⁰⁰ and Pond.¹⁰¹

Miscellaneous criteria of origin. As evidence of primary origin of some cherts, St. Clair¹⁰² cites the association of highly siliceous dolomites, suggesting that a high concentration of silica must have been present at the time of deposition. Because of the vast amount of silica in the Franciscan bedded cherts, Davis¹⁰³ believes that dilute river waters or the activities of radiolaria are inadequate to have furnished it. He regards emanations of igneous rocks or submarine siliceous springs as the only possible sources of such a great supply of silica.

Method of Field Study

The method of approach in the study of cherts that most appealed to the writer consisted of a classification of types according to general characteristics and a systematic analysis of each. The many varieties of chert represented in the Kaibab formation and the probability that at least several distinct theories of origin are applicable made this method a necessity. Certainly no broad generalization would suffice.

In the attempt to classify the cherts and other siliceous deposits of the Kaibab formation, such general features as color, texture, shape, and size were the principal ones to be considered. Since any of these characteristics may vary to a considerable degree in the same type of chert, it was thought at first that any general description would be inadequate. Detailed observations, however, showed that in each type the features as listed are remarkably regular in character for "ideal" examples and the many variations are apparently due to numerous local conditions that influence development or growth and cause divergence from the normal. Of great significance, also, is the probability that all of these cherts except those developed after consolidation and uplift of the strata are definitely related to one another as regards time of deposition and source of material, but reflect by their types particular conditions of deposition. It is natural to expect, therefore, that in intermediate areas, mixtures of conditions should produce mixtures of types.

In the systematic analysis of the various cherts recognized in the Kaibab formation, the following characteristics were recorded for each type: (1)

⁹⁸ W. A. Tarr, *op. cit.*, p. 18.

⁹⁹ W. S. T. Smith, *op. cit.*, p. 55.

¹⁰⁰ W. A. Tarr, *op. cit.*, pp. 15, 42.

¹⁰¹ W. F. Pond, in Fowler, Lyden, Gregory, and Agar, *op. cit.*, p. 52.

¹⁰² S. St. Clair, in Fowler, Lyden, Gregory, and Agar, *op. cit.*, p. 51.

¹⁰³ E. F. Davis, *op. cit.*, pp. 402-408.

color, (2) typical shape, (3) size, (4) texture, (5) presence or absence of banding, (6) nature of border, (7) presence or absence of cracks and fillings, (8) arrangement of individual chert bodies, (9) relation to bedding planes, (10) regional distribution, (11) types of fossils present, (12) type of fossil preservation, (13) nature of surrounding rock.

In the analysis of chert types it will be noted that the first four features considered, as listed above, involve purely descriptive characteristics. The other nine, however, are features that have been cited by students of chert as evidence supporting some particular theory of origin. In addition to field observations, thin-sections of each type of chert were prepared and studied.

Type 1: Spherical Concretionary Chert

(Plate 24a)

One form of chert found commonly in parts of the β member of the Kaibab formation, the origin of which seems to the writer to be fairly obvious, is here designated as type 1. It is characterized by its general gray-brown color, its concretionary form—irregular but with marked tendency toward spherical masses—its hard, dense texture, and its size, which ranges from 2 inches to 12 inches in diameter with an average of about 5 inches.

Chert of type 1 shows no banding, and neither cracks nor fillings have been observed in it. The outer surface usually marks an abrupt change and thus develops a parting plane on many weathered specimens. In some examples, however, a transition layer of "cotton rock"¹⁰⁴ intervenes.

This type of chert is found commonly in the marine phase of the β member, Kaibab formation, in the west and sparingly as far east as the Kaibab Trail in Grand Canyon. Both to the north and south of Grand Canyon the area of its distribution extends eastward about the same distance. This chert is especially well represented along the Hermit Trail section in Grand Canyon, where it is found in a massive 2-foot sandy limestone bed unassociated with other types of chert, and also below, among different types of concretions and nodules throughout 27 feet of massive ledges. The horizons at which it is found are in the upper part of the formation. Nowhere does it appear to have any relation to bedding planes or to any other observable passageways that might have assisted in the entrance of solutions.

Some of the most striking features pertaining to the concretions of type 1 chert are its associated fauna, the modes of preservation of this fauna, and the distribution of the animals in relation to the concretions. Wherever the concretions are found in well-developed form, sponge structures have been observed in the centers of a majority of them. Bryozoa and small sections of crinoids have been noted abundantly both in the surrounding limestone and along the surfaces of the chert (plate 25a). Within the

¹⁰⁴ Defined by Fowler and Lyden as a rock intermediate between chert and limestone.

concretions they are less numerous, and toward the centers they are scantily present or absent.

Similar fossils in the surrounding limestone are silicified; those along the borders or on weathered surfaces are leached out, leaving molds which preserve delicate detail, and many of those from the interior, exposed on fresh surfaces, are of calcium carbonate. Large silicified brachiopods are common in the enclosing limestone but rare within the concretions. Some excellent examples where brachiopods appear to have obstructed the growth of a concretion in one direction have been noted (plate 25*b*).

Chert fragments that were probably derived from the Kaibab formation and, judging by their angular shapes, were not transported any great distance are found as pebbles in the basal conglomerate of the Triassic Moenkopi formation in many parts of the Colorado Plateau. Where they are exposed along the road between Winslow and Long Valley, Arizona, about 6 miles northeast of the latter locality, the writer discovered several fragments of chert that contained sponge centers and were apparently derived from typical Kaibab concretions of type 1. This demonstrates clearly that type 1 chert had been formed as a consolidated rock before the beginning of Triassic deposition.

A summary of data proving that chert of type 1 was developed on the sea bottom and not after consolidation of the matrix follows: (1) the presence of chert of this type, containing sponge centers, in the basal conglomerate of the Triassic Moenkopi formation; (2) the presence of the shells of lime-secreting animals as silicified fossils or as fossil molds outside of, on the surfaces of, and on weathered faces of the concretions, but usually as calcareous fossils within the concretions; (3) the presence of large brachiopod shells in contact with spherical concretions, apparently having limited the growth or development of these concretions in their direction; (4) the distribution of lime-secreting, calcareous organisms in relation to the concretions, i. e. common in matrix and on surfaces, less common within the chert, and practically missing in central areas; (5) the distribution of concretions throughout massive limestone beds without relation to bedding planes or other channels favoring passage of solutions; (6) the general distribution of chert of this type in the formation, with no apparent concentration in areas of deformation and with entire absence in some areas of faulting and folding; (7) the location of areas of maximum abundance and development, to the west of the region containing highly saline or brackish-water deposits and faunas, and also west of that containing extensive bedded cherts, but in parts of the formation characterized by typical marine limestone and fossils.

If the chert of type 1 was deposited on the sea bottom, it is important to consider the nature and cause of its development and the possible source of the silica. Apparently a significant factor in this connection is the presence of sponge structures in the centers of a majority of examples in areas where the concretions of this type are abundant and well developed. Although these sponge skeletons undoubtedly served as nuclei in the con-

cretionary development, microscopic examination shows that the animals could not have built up through their life processes the concretions found today.

Thin-sections show that the sponge structures themselves are now in the form of chalcedony, and that residual patches of fine-grained carbonate are present in the concretions. At one place, organic structure was found to be preserved in callophane; elsewhere minute calcareous organic remains appeared to be partially replaced by silica. Most of these features point toward a replacement process. Since the chert in all probability was developed on the sea floor, a "penecontemporaneous" origin for the type 1 concretions appears to be the only logical explanation.

That the origin of type 1 chert is not organic in the strict sense of the word is illustrated by the usual large excess of silica above that in the actual sponge structures of these concretions. The sponges apparently served as centers for continued attraction of colloiddally dispersed silica, which ultimately replaced the organic matter and even much of the mineral substance, developing well beyond the limits of the siliceous skeletons. The elements for such a theory were first advanced by Prestwich¹⁰⁵ in the study of certain sponge spicules, following the work of Graham, who noticed that colloidal silica is attracted to other forms of "silex" and also "any gelatinous substance."

Negative evidence regarding the origin of the silica in the spherical concretionary chert is found in the comparatively small number of silica-secreting animals in the formation—far too few satisfactorily to account for the large amount of chert present—and in the lack of evidence of an igneous source. Some positive information on this subject is furnished by the geographical distribution and the relationships between this type of chert and certain others in the formation. Since this subject can be discussed more adequately in another connection, it is sufficient to say here that the most probable source of the silica appears to be sluggish streams which undoubtedly meandered over an extensive, flat terrain to the eastward before emptying into the sea near this area.

Type 2: Hard Nodular Chert

(Plate 24b)

A variety of chert in the Kaibab formation that apparently is closely related to the foregoing type 1 is light gray or brown in color, is very hard and dense, and commonly forms irregular nodules. These nodules have average thicknesses of about 0.75 inch and range in length between 2 and 3 inches. They commonly weather with black surfaces. They are extremely varied in shape but have a tendency toward the form of round-edged cylinders, some of them branching. The larger nodules approach more nearly a spherical shape, thus resembling concretions of type 1.

¹⁰⁵ Joseph Prestwich, *Geology, chemical, physical, and stratigraphical* (Oxford: Clarendon Press), pp. 320–324, 1886–1888.

Thin-sections show a general similarity between these cherts and those of type 1. In both, the matrix is mainly chalcedony but contains irregular patches of fine-grained carbonate. Likewise, small detrital quartz grains and euhedra of dolomite are scattered through both types.

In distribution also the nodular cherts which are designated as type 2 are similar to the cherts of type 1 but are somewhat more widespread. Along the Hermit Trail in Grand Canyon they are typically developed at several horizons in the upper part of the β member. At one horizon they are intermixed with the spherical concretions of type 1, but in others are present alone.

It seems highly probable that cherts of type 2 represent a variety of type 1 which, because of some local condition, were not permitted to develop into the "normal" spherical shape. The evidences for this opinion are found in (1) the presence of sponge structures in the centers of some individuals, (2) the general similarity of distribution of the two types, (3) the examples of intermediate forms where these types are found together, (4) the similar relationships to the beds that enclose them and to surrounding and enclosed calcareous fossils, and (5) similarities in general character as seen in thin-section.

Type 3: Quartzitic Chert, Concretions, and Irregular Layers

(Plate 27c)

One of the most unusual types of siliceous deposits in the Kaibab formation is in the calcareous sandstones and sandy limestones that form the lower portion of the β member over a wide area. These silica deposits have been developed commonly in the form of round concretions, irregular globular masses, or even in places as thin layers which, because of smooth, dark brown weathered surfaces, stand out in contrast with the usual gray pitted surfaces of the matrix. The concretions formed by these siliceous deposits commonly range from 4 to 10 inches in diameter. Many layers have the appearance of connected series of concretions, but others cannot be identified as such, being more or less consistent in thickness (average 6 inches) but with irregularities above and below.

The siliceous deposits under discussion are here designated as cherts of type 3 because they appear to be definitely related to the true cherts of the formation, but it must be pointed out that both in the hand specimen and under the microscope, they are quartzitic in nature. Petrographic examination shows that most of the rock of this type is composed of subangular quartz grains secondarily enlarged to give compact quartzitic character (plate 26b). Sponge skeletons which are in the centers of some of these concretions are composed of chalcedony as in type 1 chert. Subangular quartz grains are packed closely around them and fine-grained carbonates occupy many intergranular spaces. Small dolomite rhombs, numerous throughout, replace quartz.

Because some of the concretionary forms of the quartzitic deposits show sponge structures in their centers similar to those within the spherical cherts of type 1, it seems probable that these at least were formed in the same manner as type 1, but on a sea bottom of different character. In brief, where sponges attracted colloidal silica from the sea waters over a limy bottom, chert concretions resulted. On the other hand, where the bottom was composed of elastic quartz, the natural result when sponges played a similar rôle was the development of quartzitic concretions due to the binding of the quartz grains with silica.

Probably the irregular, layer deposits of type 3 chert either are accumulations of quartzitic concretions with sponge nuclei, developed close together, or are layers of silica deposited on the sea floor from supersaturated waters without nuclei to localize distribution. Thus quartzitic layers also appear to have been formed merely by a cementation of elastic grains.

Further evidence of the similarity in origin of type 1 and type 3 cherts is found in the distribution of each in massive beds and without relation to bedding planes or fissures. Furthermore, it is significant that where the fossils of lime-secreting animals are found within the quartzitic concretions of type 3, they are usually represented by molds which preserve minute details. *Chonetes* preserved in this manner are extremely common.

Type 4: Brittle, Bedded Chert

(Plate 27a, b)

Along the Kaibab and Bright Angel Trails leading into Grand Canyon from the South Rim and in a narrow belt extending north and probably also south from this area, the β member of the Kaibab formation is characterized chiefly by alternate beds of sandy limestone and earthy, white chert (plate 27b). In general this belt lies between an area of calcareous sandstone largely free of chert to the east and one of crystalline limestone containing abundant chert concretions and nodules of various types—including types 1, 2, and 3—to the west.

The chert of the bedded variety here designated as type 4 has very distinctive characteristics. On the weathered as well as on fresh surfaces, it is dull white, in places almost chalky, but weathering commonly produces a yellowish coating or stain. The chert is hard but very brittle, and as a result locally causes the development of conspicuous recesses in otherwise massive ledges of the β member, Kaibab formation.

The individual beds of chert of type 4 range in thickness from a few inches to a maximum of about 10 feet. The average in typical sections is about 3 feet. Within each bed are numerous tongues and irregular lenses of a tan-colored, dolomitic siltstone, or, less commonly, a fine-grained sandstone. The chert itself shows no evidence of lamination, but parting planes separate the principal beds from the sandy limestone or siltstone beds above and below. These planes are usually horizontal, but in places they con-

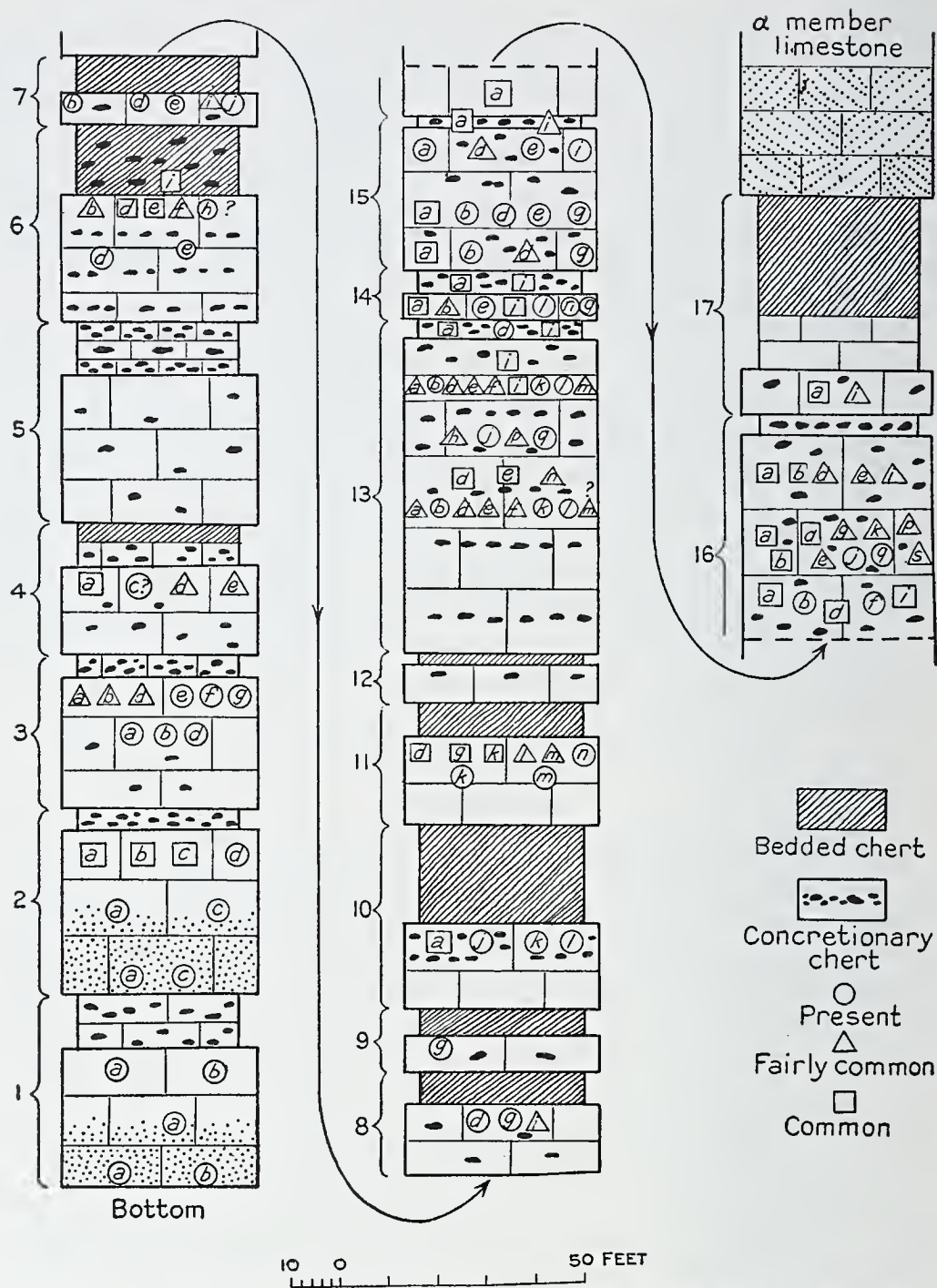


FIG. 24. Location and relative abundance of marine fossils, Kaibab β member, Bright Angel Trail, Grand Canyon

- a. Crinoids
- b. Bryozoa
- c. *Chonetes kaibabensis*
- d. *Productus bassi*
- e. *Productus occidentalis*
- f. *Derbya* sp.
- g. *Composita* sp.
- h. *Avonia* sp.
- i. Sponge

- j. *Aviculopecten* sp.
- k. *Squamularia* sp.
- l. *Chonetes subliratus*
- m. *Marginifera* sp.
- n. *Meekella* sp.
- p. *Pugnoides* sp.
- q. *Lophophyllum* sp.
- r. *Waagenoconcha* sp.
- s. *Spiriferina* sp.

verge to form wedges of the chert beds or they curve as basins that are filled by sloping laminae of clastic sediments (plate 27a).

A cyclic deposition has developed in areas where the bedded, earthy cherts are common. It consists of rhythmic repetition of the following sequence from bottom to top: (1) earthy chert bed several feet thick; (2) barren sandy limestone or calcareous fine-grained sandstone of similar thickness; (3) highly fossiliferous (brachiopod, bryozoan, crinoid faunule) sandy limestone or calcareous sandstone of similar thickness. See figure 24.

Complete cycles of this nature, repeated seven or more times, are well represented along the Bright Angel Trail in Grand Canyon, but farther east, below Yaki Point, the fossiliferous member of the cycle is usually missing and the two other divisions alternate.

In thin-section the bedded cherts show silica present in three stages: first, a greater or less amount of small, subangular, detrital quartz grains scattered throughout; second, chalcedony, which in pure specimens makes up most of the rock, but elsewhere contains residual patches of carbonate or is present in the form of bands, alternating with others of detrital quartz and of carbonate; third, a secondary quartz of medium size which occurs in a comb structure in local cracks and fissures. Small dolomite rhombs are everywhere numerous and are found invading the quartz and possibly also the chalcedony.¹⁰⁷ Samples of the brown siltstone that forms tongues and lenses in the chert beds show similar detrital quartz but in greater abundance, and in addition include carbonates (with abundant euhedral dolomite) but little chalcedony. From this examination it appears that the chalcedony is later than the detrital quartz and the dolomite probably still later.

Evidence has been given by Sagin¹⁰⁸ to indicate that precipitation of silica is based on changes of alkalinity during deposition, and he suggests that $MgCO_3$ is a factor in the process. If this theory is correct, certainly the high magnesium content of this part of the Kaibab formation indicated by chemical analyses would suggest very favorable conditions for the deposition of silica. It may be significant that the chert beds are in contact with limestone and sandstone containing much $MgCO_3$.

An inorganic origin is postulated for type 4 chert, largely on the basis of the lack of organic remains in it. The only suggestions of fossils are some locally distributed but abundant small tubular structures which may represent worm borings. The supposition that this chert developed on the sea floor rather than by replacement following consolidation of the sediments is supported by (1) its distribution entirely without respect to regional or local deformation, (2) its presence in the angular conglomerate at the base of the Triassic, and (3) its repetition in the section as a part of

¹⁰⁷ For a similar case of carbonates replacing quartz see C. W. Honess, *Geology of the southern Ouachita Mountains of Oklahoma*, Okla. Geol. Surv. Bull. 32, pt. I, pp. 43, 53, 192, 1923.

¹⁰⁸ C. L. Sagin, *The Cameron Apennine—chemical origin of the Cretaceous flints*, Min. Met. Chim., vol. 61, pp. 95–98, 1924.

a cycle of deposition. Probably the most convincing evidence pointing toward an inorganic origin on the sea bottom is found in its distribution in relation to that of other types of sediments, including other varieties of chert, and also to the different faunules of the Kaibab formation. This feature is described and discussed under "The Distribution of Kaibab Chert and Its Significance" (page 96).

Tarr¹⁰⁹ advanced the theory that chert is formed from silica taken into solution as a colloid by streams and carried to the sea, where it accumulates, partly owing to protective or hydrophilic sols, and is finally precipitated quite rapidly. This seems to explain best the features observed in the field of type 4 chert of the Kaibab formation. Only in the final step does it seem desirable to diverge from Tarr's theory. At this stage it appears necessary to postulate replacement of the "penecontemporaneous" type in order to explain the various features of replacement seen in thin-section. Furthermore, Tarr's statement that such conditions are best developed "during periods of low-lying lands" is in keeping with known conditions of the Permian in western America.

Types 5, 6, and 7: Miscellaneous Varieties of Chert, of Sea-Bottom Origin

Several varieties of chert, other than those already described, are found in the Kaibab formation as definite types, considered to be of sea-floor origin because of their general similarity in manner of development, in distribution, and in many physical characteristics to those previously discussed. Three of these chert types are here briefly described, but no attempt is made to explain the exact conditions or controlling factors involved in their origin, since they do not show enough distinctive characteristics to warrant conclusions along these lines. Probably a number of other definite types in this category might be recognized in various parts of the formation, but they are so limited in distribution that there would be no particular value in describing them here.

Type 5 chert is a conspicuous blue-gray variety which forms a definite bed in the lower part of the β member as seen along the Hermit Trail in Grand Canyon. Although of a bluish color on the fresh face, it weathers to a yellow-brown surface nearly matching that of the surrounding siltstone. Within the main zone, 5 feet thick, the chert forms innumerable irregular tongues and lenses which bulge and taper steeply (plate 29a). Separating these are very thin beds (0.125 to 0.25 inch) of yellow-brown siltstone which slope, thicken and thin, and curl to fit the irregular surface on which they lie. Whether this irregularity is the result of deposition on a surface covered with mounds or is due to later compaction could not be determined. The ratio of chert to siltstone included in the zone is roughly 10 to 1.

The blue cherts of type 5 are hard and dense, but brittle. This feature

¹⁰⁹ W. A. Tarr, *The origin of chert and flint*, Univ. Missouri Studies, vol. 1, no. 2, p. 24, 1926.

suggests, as does also the bedded nature and an entire absence of fossils, a relationship to type 4, which is thought to have formed from deposition of silica in a colloidal condition from supersaturated waters. Numerous cracks in these cherts, sealed by fillings of white calcedony, are certainly secondary developments, but a zone of breccia—chert fragments in a matrix of yellow sandstone—about 6 inches below the top of the zone in one place is more difficult to explain. Very probably it is a type of intraformational conglomerate.

Type 6 chert of the Kaibab formation is a dark gray variety, brown on weathered surface, which characteristically is developed as ellipsoidal concretions. An average size is 2 inches by 3 inches by 4 inches. Its texture is dense and it is hard and tough. As in the case of other concretionary cherts already described, the individuals form layers in definite zones, showing no relation to bedding planes and being isolated from the major ones. The concretions are oriented with the longer dimensions on the horizontal plane. No fossils are found in association unless certain small red and white blotches, which are common, represent organic remains. The surrounding sandy limestone is a massive rock below, but above is finely laminated, each bed curving about the concretions as though deposited over them. This type of chert is well developed in the upper part of the β member on the Kaibab Trail in Grand Canyon.

Type 7 chert of the Kaibab formation is undoubtedly related to type 6 but is light gray to white in color with a dull, earthy appearance. It forms an almost continuous layer of connected ellipsoidal concretions. The layer averages from 2 to 4 inches thick. The chert itself is hard and dense and commonly has a thick outer layer of "cotton rock." As in the case of type 6 chert, it is surrounded by a yellowish, sandy limestone and no fossils are found either in it or in the surrounding rock.

In this and also in the two preceding chert types, thin-sections show that the silica is principally chalcedony, that detrital, subangular quartz grains are scattered throughout in varied degrees of abundance, and that dolomite rhombs are usually numerous. In several examples carbonates replace detrital quartz as in chert of types 1 and 4.

Type 8: Yellow and Red Bedded Chert

Along the South Rim of Grand Canyon in numerous places, notably near the head of Hermit Trail, on Hopi Hill, and on Lipan and Desert View Points, a ledge of beautiful red, yellow, and white chert is a very conspicuous feature. At a similar horizon (at the top of the β member of the Kaibab formation) the same highly colored type of chert is found 70 miles northeast of Grand Canyon near Lees Ferry, and it has been observed in numerous localities eastward along the Little Colorado Canyon and also on the surface of the Mogollon Plateau, 100 miles and more to the south.

The beds of yellow and red chert, here designated as type 8, range in thickness from about 2 to 17 feet at different localities examined. In most

exposures the rock shows physical characteristics between those of jasper and chalcedony and is hard and resistant, but in some outcroppings it is dull and earthy and extremely brittle.

The unique character and brilliance of color of type 8 chert early led the writer to consider it an excellent marker bed in the formation, especially since it is conveniently located near the top of the β member. Difficulties were soon encountered, however, when it was found that this highly colored chert is entirely lacking in certain sections which include both α and β members and which are situated between sections containing the chert. Further complications arose when, in measuring a section along the Little Colorado Canyon east of Grand Canyon, the writer found yellow and red chert at two distinct horizons instead of one.

A satisfactory explanation for the type 8 chert was found when the writer traced laterally a typical yellow and red bed of this type and found that in a fresh exposure its character was changed completely. Here the chert was dull white, earthy, and brittle, resembling type 4. Later, all intermediate stages between the two types of chert were found. With a knowledge of these relationships in mind and a realization that the yellow and red phase is found only near or on the plateau surface where the elements have been at work far longer than on the cliff faces below, it appears obvious that the change from brittle to resistant rock and the oxidation in this rock are the direct results of weathering. Possibly this secondary development is brought about by replacement of the calcareous elements in type 4 chert by more silica and by an oxidation of the contained iron, thus accounting for the added strength and color in the rock.

Type 9: Gray and White Banded Chert

(Plate 29b)

A type of siliceous deposit that has limited distribution in the Kaibab formation but is remarkable because of its physical character and mode of development is a banded variety at the base of the α member of the Kaibab formation where it is exposed along the Hermit Trail of Grand Canyon. The silica of this type is milky white in color and is translucent to opaque. It appears, where seen on the face of a ledge, as a series of bands each averaging about 0.125 inch thick and separated by bands of dull gray sandstone of about the same thickness. The banded zone ranges from 2 to 5 inches. Individual bands are extremely variable both vertically and laterally, showing many changes in thickness in short distances and being curved and warped locally.

The origin of type 9 chert, as the banded variety is here designated, seems obvious. In numerous places it is replacing limestone which apparently had been deposited between thin laminæ of sandstone. Everywhere its development has been limited by the irregular bedding surfaces of the enclosing sandstone. The extremely erratic character of the laminæ of

both sandstone and chert (or limestone) suggests original deposition by currents of rapidly changing character. The replacement is easily explained when it is noted that the banded zones invariably are located at the top of massive sandstone units and immediately below major horizontal parting planes.

Silicified Fossils, Secondary Origin

Throughout the marine phases of the Kaibab formation the silicified shells of lime-secreting organisms are everywhere abundant on rock surfaces. That silica in this form is the result of replacement is obvious, but the time of this replacement is frequently not appreciated by the casual observer.

In several places in the massive fossil-bearing beds of the marine portions of the Kaibab, the writer has had opportunity to examine fossil specimens from the body of the rock well beneath the weathered face and away from joints and bedding planes. In every example the brachiopods and bryozoa were not silicified on the fresh exposures, but the depth beneath the surface to which the secondary action had penetrated, varied with the enclosing rock.

At Clover Creek, between Flagstaff and Pine, Arizona, shells of the genus *Chonetes* are extremely abundant in certain limestone ledges in the Kaibab. On the surface they are everywhere well silicified, but one or two inches beneath, they remain calcareous. At Fossil Mountain in Grand Canyon, several species of brachiopods obtained from depths about 6 inches beneath the weathered face of a massive limestone proved to be calcareous and, in at least two examples, to retain what is thought to be the original color. Whether or not this is actually the case it is impossible to say, but from the condition of these shells and the rocks which enclosed them, this seems probable. The specimens referred to, *Chonetes kaibabensis*, are a beautiful pale pink in color. Apparently such a find is of uncommon occurrence.¹¹⁰

Quartz Geodes, Secondary Origin

Quartz geodes, oval in cross section, are abundant in many parts of the Kaibab and Toroweap formations, especially in those facies that are highly magnesian in character. In a few examples evidence is clear that a fossil shell has been responsible for the development in a particular place, although in most cases the origin of the cavity that has been lined with quartz is not apparent. From the usual lack of fossils in certain dolomitic limestones which are replete with geodes in such localities as Walnut Canyon and Badger Canyon, it seems probable that most of these geodes mark the places formerly occupied by mollusks.

¹¹⁰ John B. Reeside Jr., *A Cretaceous pelecypod with color markings*, Jour. Wash. Acad. Sci., vol. 20, no. 4, p. 59, 1930.

The Distribution of Kaibab Chert and Its Significance

The cyclic sedimentation involving the bedded chert of type 4 (page 91) suggests a definite relationship between that chert and the fauna of the enclosing limestone. Lack of fossils in the chert beds points to the supposition that, as the sea waters became supersaturated with silica and thus began to deposit it in a colloidal condition on the ocean floor, conditions were unfavorable to the existence of lime-secreting animals. The nearly barren sandy limestone beds above must then represent calcareous deposits formed during the interim following the deposition of silica and before the marine organisms had reclaimed the area as their habitat. Still later, as these calcareous deposits continued to be laid down on the sea floor, animals entered and became prolific in the area, thus completing the cycle. A new cycle began when the silica in the water again approached a state of supersaturation and animal life was again eliminated in the area, presumably as far westward as the margin of normal marine waters. See figure 24.

The relation of the bedded cherts (type 4) to their lateral equivalents is perhaps just as significant as the vertical sequence of sediments just discussed. The fact that, toward the east or in the direction of the ancient shore line, these cherts and the accompanying sandy limestones are replaced by sandstones with a molluscan fauna of totally different character suggests that the waters were less saline or even brackish toward the shore line. Probably a great river with fine sediments entered the sea in this area. Westward toward the open sea, on the other hand, the sandy limestones merge into purer limestones and the bedded cherts are replaced first by definite layers of chert concretions of various types and, still farther west, by concretions of similar types scattered largely at random through the entire limestone member.

The most logical interpretation of the distribution of Kaibab β deposits, the writer believes, is as follows: Out in the open sea, sponges were sufficiently numerous constantly to attract silica from the water, therefore they caused chert concretions to be formed and prevented the silica solution from attaining a supersaturated state with resulting deposition of chert beds. Farther east, where river and marine waters mingled, beds of chert were laid down, but still farther toward the shore, near the mouths of rivers, the water was too much in motion and too fresh to deposit silica.

Rivers may furnish silica to the sea in considerable amounts. According to Clarke,¹¹¹ the average dissolved silica content in the rivers of the earth today is 11.67 per cent of the total solids in solution (probably much greater in the Arizona-Utah region during the Permian period because of extensive flat terrain), yet the amount of silica in sea water is calculated by Murray and Irvine¹¹² to be only 1 part in 200,000 to 1 part in 460,000 parts of sea water. It is obvious from these figures that the silica con-

¹¹¹ F. W. Clarke, *The data of geochemistry*, U. S. Geol. Surv. Bull. 770, p. 119, 1924.

¹¹² J. Murray and R. Irvine, *Proc. Roy. Soc. Edinburgh*, vol. 18, p. 236, 1891.

tributed to the sea by streams or other sources does not long remain in solution. It must be either taken up by living organisms or chemically precipitated.

Probably the source of the silica in the chert deposits of the Kaibab formation was the flat desert terrain that existed during the Middle Permian epoch over a vast area to the east of Grand Canyon. That region during the time of Kaibab deposition apparently was a plain or relatively flat surface developed by the accumulation of extensive red beds and other sandy deposits, a geographic feature which probably is not duplicated in the world today.

At least one of the rivers that meandered over this surface apparently emptied its content of silt and silica into the sea in the vicinity of eastern Grand Canyon. This is indicated by the fact that in this area traces of a near-shore, "brackish water" fauna (molluscan) are found preserved in a fine-grained sandstone, whereas to the south in the Mogollon Plateau region and to the north in eastern Utah sections, fossil representatives of the same age are largely associated with impure limestones formed also along the margins of the sea.

A second evidence that during deposition of the Kaibab formation the mouth of a large river occurred in the proximity of eastern Grand Canyon is found in the location of the bedded cherts (type 4) in an area where fresh waters apparently first mingled with marine waters as indicated by both sediments and fossils. In such a locality, as pointed out by Davis,¹¹³ the localization of cherts derived from river deposits should be expected.

Comparison with Cherts of the Phosphoria Formation

North of the area of Kaibab sediments is a great Permian marine basin extending from Wyoming to Oregon and from Canada to central Utah in which various types of deposits were accumulated (figure 25). These sediments are known as the Phosphoria formation.

The Phosphoria formation has attracted the attention of geologists largely because of the economic aspect of the phosphate deposits which it contains, and also because of the chert which constitutes major portions of the formation in certain areas. Studies of the Phosphoria have been made by Blackwelder,¹¹⁴ Schultz,¹¹⁵ Condit,¹¹⁶ Mansfield,¹¹⁷ Branson,¹¹⁸ and others.

¹¹³ E. F. Davis, *The radiolarian cherts of the Franciscan group*, Univ. Calif. Pub., Bull. Dept. Geol., vol. 2, no. 3, 1918.

¹¹⁴ Eliot Blackwelder, *New geological formations in western Wyoming*, Jour. Wash. Acad. Sci., vol. 8, pp. 417-426, 1918.

¹¹⁵ A. R. Schultz, *A geologic reconnaissance of the Uinta Mountains, northern Utah, with special reference to phosphate*, U. S. Geol. Surv. Bull. 690, 1919.

¹¹⁶ D. D. Condit, *Phosphate deposits in the Wind River Mountains, near Lander, Wyoming*, U. S. Geol. Surv. Bull. 764, 1924.

¹¹⁷ G. R. Mansfield, *Geography, geology and mineral resources of parts of southwestern Idaho*, U. S. Geol. Surv. Prof. Paper 152, 1927; *Some problems of the Rocky Mountain phosphate field*, Econ. Geol., vol. 26, no. 4, 1931.

¹¹⁸ C. C. Branson, *Paleontology and stratigraphy of the Phosphoria formation*, Univ. Missouri Studies, vol. 5, no. 2, 1930.

Both the Kaibab and Phosphoria formations are considered to be of Middle Permian age, and their northernmost and southernmost exposures, respectively, are in close proximity, hence it is thought desirable to compare their extensive chert deposits. According to Mansfield,¹¹⁹ the Rex chert of



FIG. 25. Tentative map of Phosphoria Sea. Modified from Schuchert's palæographic map of the Permian. (From Mansfield.)

the Phosphoria is massively bedded with very fine, even texture except near the base, where, at some localities, is found a coarser-textured bed composed largely of the spicules of siliceous sponges. "No laminæ of shale have been observed in it but bedding planes are well developed." Also he states that "the massively bedded facies alone ranges from about 60 to 110 feet in thickness and appears to have been in simultaneous process of formation throughout much of the great area occupied by the Phosphoria formation." In it the only fossils known are a few casts of crinoid stems, preserved in delicate detail.

¹¹⁹ G. R. Mansfield, *Geography, geology and mineral resources of parts of southwestern Idaho*, U. S. Geol. Surv. Prof. Paper 152, pp. 368-369, 1927.

The bedded chert deposits of the Phosphoria are located in the central portions of the area and are essentially free of fossils. Both to the east, from the western Wyoming border southward into Utah, and to the west, in southwestern Idaho and eastern Oregon, are limestones containing brachiopod faunas which are considered by Mansfield to be of the same age as the chert beds. In the eastern district these limestones lie above the phosphate deposits, suggesting that normal marine waters succeeded the foul waters in which presumably the phosphate beds were formed.

"Some method of chemical precipitation" is considered by Mansfield "as the most probable mode of accumulation of the [Rex] chert"¹²⁰ and he inclines strongly toward the principles of Tarr's theory as the most logical for explaining the unusual features (extensiveness and occurrence in beds) of the Rex. The source of this tremendous amount of silica, however, he believes is probably to be found in the materials derived from volcanic activity in the area. Volcanism is indicated (1) by volcanic tuff of that age in central Idaho¹²¹ and (2) by the fluorine content in the phosphate rocks,¹²² suggesting the presence of siliceous springs.

The chert deposits of the Phosphoria are found in an area between marine deposits with brachiopod faunas, whereas in the Kaibab formation the bedded cherts (likewise believed to be deposits of the sea floor) are to the east or shoreward of the marine limestones containing a brachiopod fauna. At first thought this contrast seems to be anomalous. The apparent inconsistency, however, may be explained by the probable difference in source of the silica. In the case of the Phosphoria the silica is believed to have been supplied by volcanic activity, which probably centered near where precipitation took place, in the geographical center of the formation. In the Kaibab, on the other hand, the silica was presumably introduced by rivers from the flat, arid land surface near by, and naturally was precipitated where these rivers encountered the marine waters. Furthermore, the contrast in the amount of silica deposited in these two areas (vastly greater in the Phosphoria) is consistent with this supposed difference in source.

Comments on Certain Kaibab Cherts in Western Arizona and Southern Nevada

The writer has had no opportunity to make detailed studies of cherts in the extreme western exposures of the Kaibab formation, but he has there observed several types that are sufficiently different in character from those already discussed to justify mention at this place. The following information was obtained during reconnaissance trips to Nevada and western Arizona sections.

¹²⁰ *Ibid.*, pp. 371-372.

¹²¹ C. P. Ross, in G. R. Mansfield, *Some problems of the Rocky Mountain phosphate field*, Econ. Geol., vol. 26, no. 4, p. 362, 1931.

¹²² This is considered to be independent evidence of volcanic activity on a large scale, inasmuch as volcanic emanations are thought to be the principal source of fluorine in the sea. See *ibid.*, p. 366.

Plate 30 shows three unusual forms of chert that are common on the Shivwits Plateau. Plate 30*a* illustrates a banded type, dark brown on weathered but pure white on fresh surface, which is present throughout a buff limestone bed in the α member. Red beds lie above and below the chert-bearing limestone, suggesting that it is a tongue formed during a short invasion of marine waters from the west. Plate 30*b* illustrates a type of chert that has the form of concentric layers around a central sphere. It is very common in the topmost limestone bed of the β member at Parashant Canyon and shows a pattern of structures commonly attributed to algal growth. Plate 30*c* shows an exceptionally large example of concretion from the middle portion of the β member. It appears to be similar to but larger than the concretions of type 1 chert farther east.

In the Goodsprings Quadrangle, Nevada, where the westernmost known exposures of the Kaibab are found, the surface of this formation from bottom to top is essentially covered with cherty material. It forms irregular bands, masses, and nodes (plate 30*d*) and weathers to a brown or black surface which imparts a dark appearance to the entire formation. In many places the chert gives the impression of being entirely a surface feature of the rock.

These cherts are described merely as a matter of record. No attempt has been made to speculate on the nature of their origins in the absence of detailed study.

RED BEDS

Description

In the Toroweap formation especially but also in the Kaibab, red beds constitute a large percentage of the total deposits. Almost the entire γ and α members in the western phase of the Toroweap formation and, in places, much of the α member of the Kaibab formation come under this category. The red beds of these formations for the most part are composed of fine quartz grains weakly cemented by a red iron oxide. Generally speaking they show either very poorly developed bedding or none at all, and in many places, especially in the α member of the Toroweap formation, they are characterized by gnarly or contorted beds and by local breccias. The western facies of each red-bed member contains gypsum beds, thin chemically precipitated limestone beds, and travertines; eastward these red beds display fine cross-lamination patterns and lose their deep red color.

Mechanical analyses of twelve typical samples of the Toroweap red beds collected at various horizons and localities between Fossil Mountain and Yaki Trail in Grand Canyon show that, in this area, they are composed largely of very fine sand (0.125 to 0.062 millimeter) and silt (under 0.062 millimeter), but contain some sand grains of greater size (0.5 to 0.25 millimeter). Only two of the twelve samples analyzed showed over 2 per cent of the total grains above the grade of fine sand (see figure 26).

These mechanical analyses illustrate the textural character of red beds

in facies 2 of the Toroweap formation, α member. For comparison attention is next directed to analyses of typical samples of the same member from Aubrey Cliffs and La Verkin, Utah, farther west (figure 27). These show much finer texture, with grains dominantly under 0.062 millimeter.

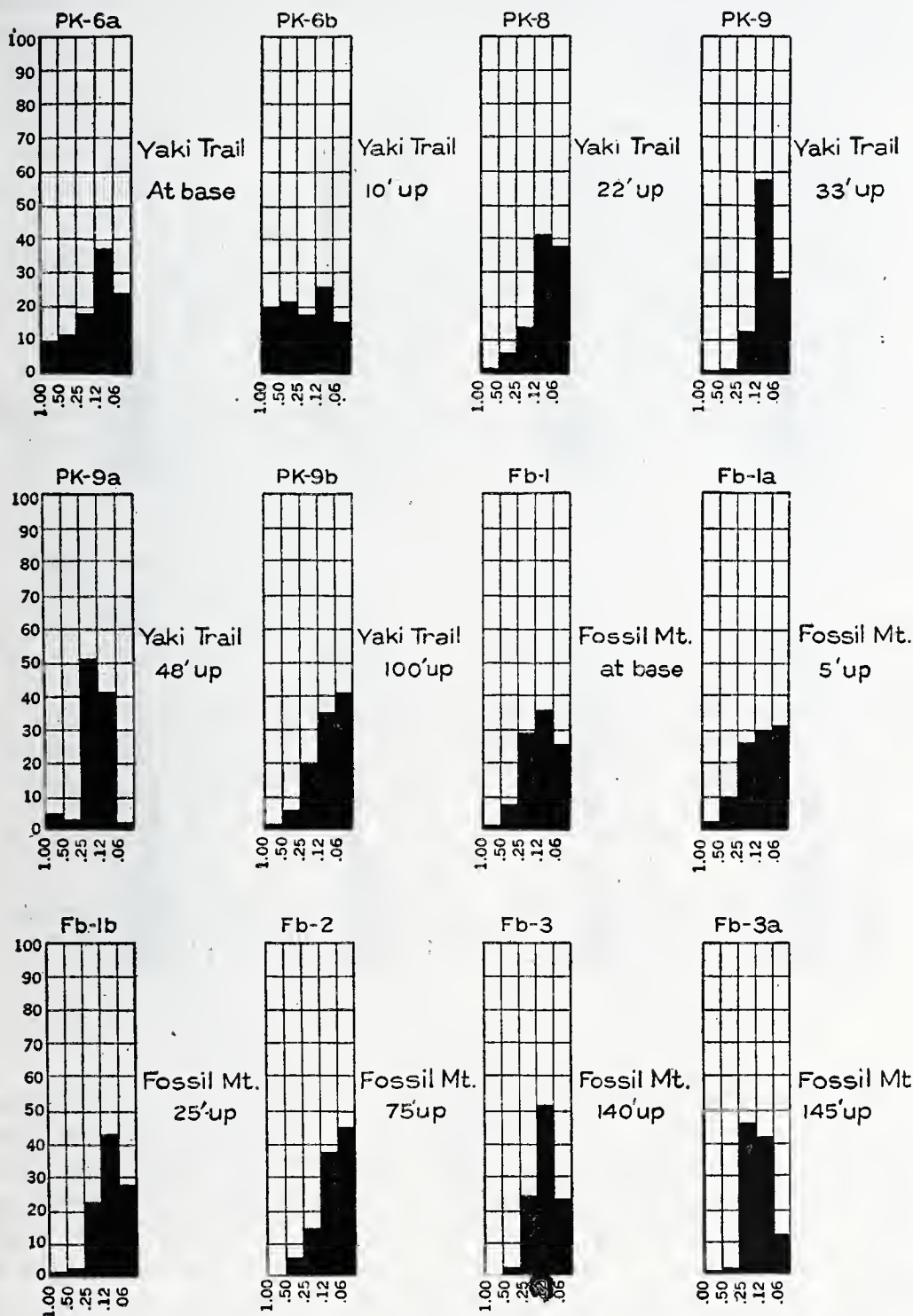


FIG. 26. Red beds of α member, Toroweap formation .

Numerous other samples of red-bed material from the western portion, facies 1, of this member were obviously so near 100 per cent silt and clay (grains under 0.062 millimeter) in composition that screen tests were not attempted. This was found true of material from Goodsprings, Nevada; Hurricane, Utah; and the Shivwits Plateau, Arizona. No material comparable in coarseness to that found farther east in facies 2 was noted in any of these localities.

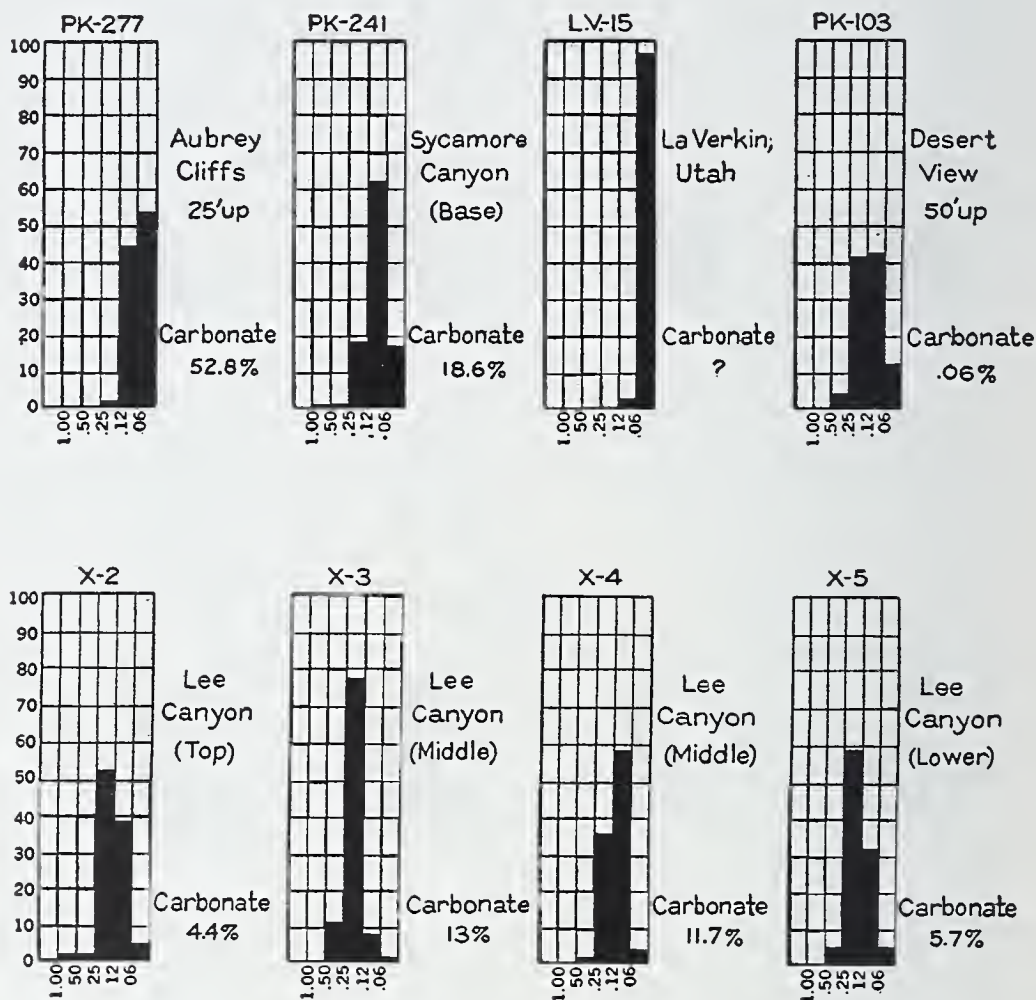


FIG. 27. Red beds of α member, Toroweap formation

From the preceding discussion it is obvious that grain size diminishes from east to west or from facies 2 to facies 1 in the red beds of the α member, Toroweap formation. Eastward from facies 2 in corresponding units of the eastern phase of the formation other textural changes are significant. Mechanical analyses of samples from Lee Canyon and from Desert View show no appreciable increase in maximum size, but disclose a decided decline in amount of silt and mud. Apparently contemporaneous with this loss of very fine material was a loss of red color and a development of well-

defined scour-and-fill cross-lamination in the beds. These features are discussed under "Light-colored Sandstones" (page 121).

The east-west transition in texture and character of sediment found in the red beds of the α member of the Toroweap formation is very probably

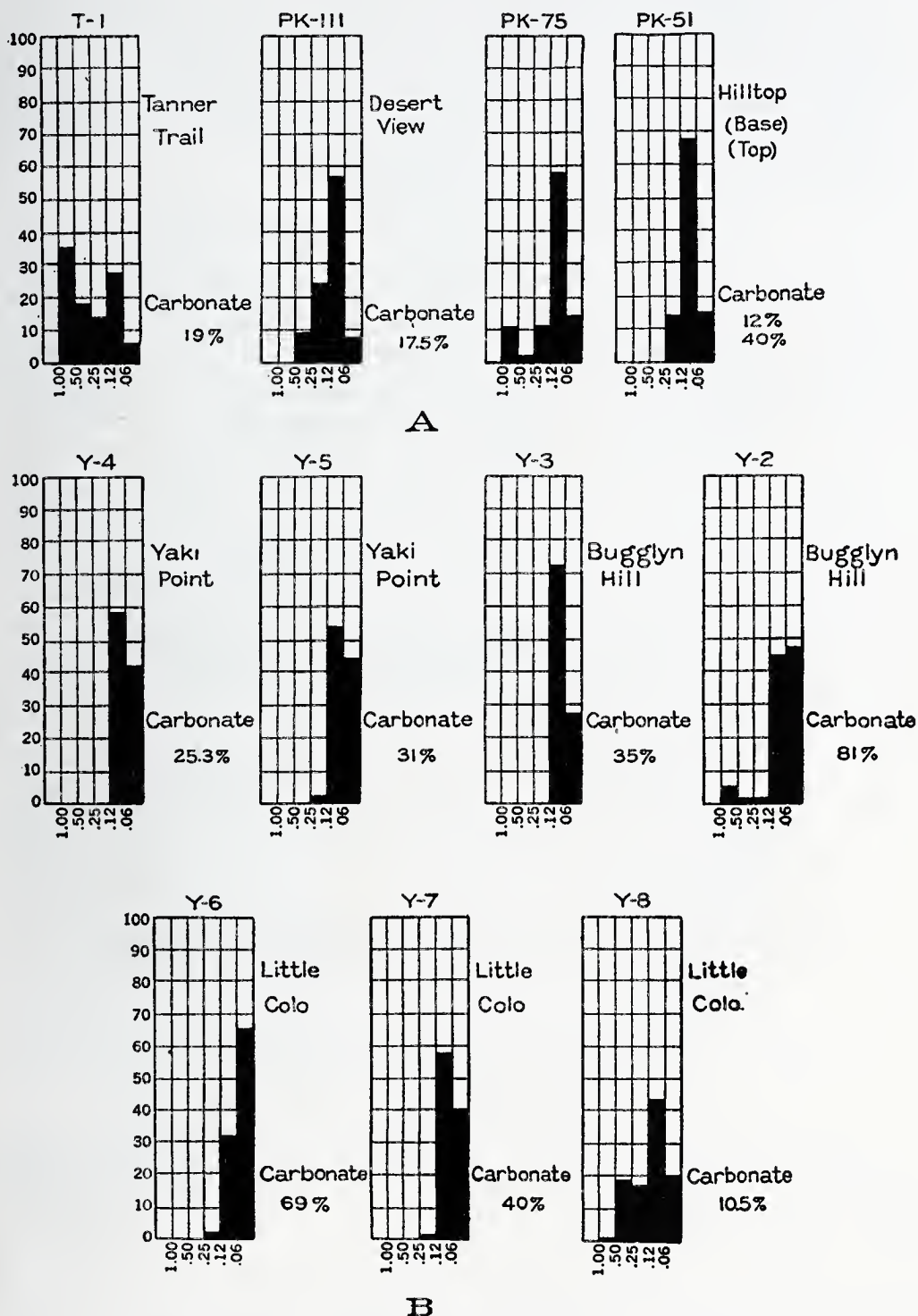


FIG. 28. A. Red beds of γ member, Toroweap formation
B. Red beds of α member, Kaibab formation

also represented in the red beds that form large parts of the Kaibab α member and the Toroweap γ member, although the record of its presence is not so clear in these members. Figure 28 shows that, in the Kaibab α member, the silt and mud stage extends much farther eastward than in either of the other red-bed members and implies a more extended sea, a supposition indicated also by extensive associated limestones. On the other hand, in the Toroweap γ member the cross-laminated sandstone stage extends farther west (below Desert View in Grand Canyon) than in either of the other red-bed members. A summary of this relationship of stages in each of the red-bed units is given in table 11.

TABLE 11. SUMMARY OF STAGES IN RED-BED MEMBERS

	Western Grand Canyon	Central Grand Canyon	Eastern Grand Canyon	Little Colorado
Kaibab α . . .	Silt, mud, gypsum stage	Silt and mud stage	Silt and mud stage	Silt and mud stage
Toroweap α .	Silt, mud, gypsum stage	Silt, mud, gypsum stage	Fine sandstone stage	Cross-laminated stage
Toroweap γ .	Silt, mud, gypsum stage	Fine sandstone stage	Cross-laminated stage	.....

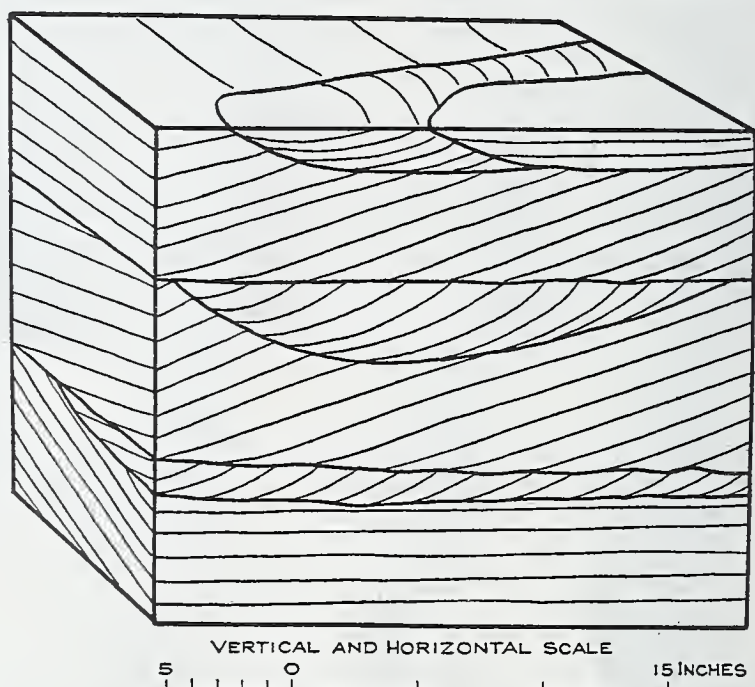
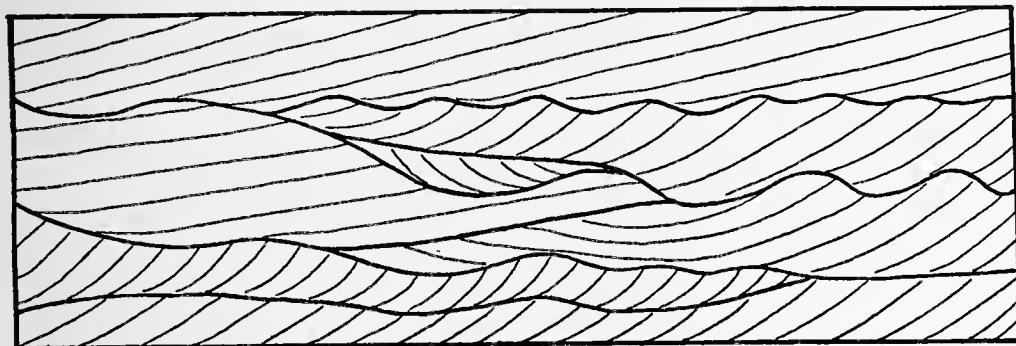


FIG. 29. Succession of planations and plane-slope deposits with scour-and-fill development within each. Pink sandstone, Toroweap γ , Tanner Trail. Block diagram from 3-dimension field sketch.

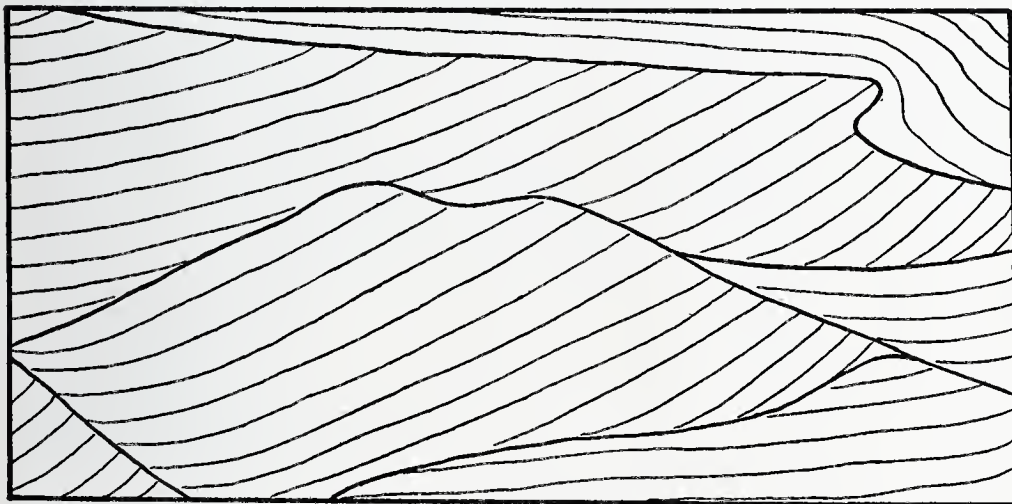
In making mechanical analyses, all samples of the red beds from the Toroweap and Kaibab formations were found to be more or less calcareous, the percentages of soluble materials ranging from 5 to 68 per cent. How

much of this was primary and how much secondary could not be determined. Petrographic examination of thin-sections and of heavy mineral concentrates indicates that the general lack of minerals other than quartz, rather than the presence of any unusual species, is a significant feature.



VERTICAL AND HORIZONTAL SCALE
5 0 20 INCHES

FIG. 30a. Small-scale scour-and-fill cross-lamination in pink sandstone, Toroweap γ , Tanner Trail below Cedar Mountain



VERTICAL AND HORIZONTAL SCALE
5 0 5 INCHES

FIG. 30b. Small-scale scour-and-fill cross-lamination in pink sandstone, Toroweap γ , Tanner Trail below Cedar Mountain

Apatite, biotite, magnetite, limonite, tourmaline, rutile, chlorite, zircon, muscovite, plagioclase, microcline, sericite, epidote, and titanite were found in small quantity in various samples, but in general all of these were uncommon.

Significance of Gnarly Bedding

The irregular, gnarly bedding so characteristic of the Kaibab and Toroweap red beds over much of the eastern part of the area in which they are

found (plate 5*b*) is a feature that is difficult to interpret with any degree of certainty. Thick, massive beds are wavy and contorted, and within short distances show marked variations in thickness without any apparent relation to beds above or below. The general structure has a definite similarity to certain beds in the Carmel formation (Jurassic) of Utah, which Baker has illustrated and described as being "in many places contorted in a fashion hard to explain except as due to flowage of unconsolidated, water-saturated materials."¹²³

That the gnarly beds in the red-bed series of the Toroweap formation represent a form of soft-rock deformation as defined by Rettger¹²⁴ seems reasonably certain. According to definition, this differs from contemporaneous deformation¹²⁵ in that it may take place at any time after the rock has been deposited and before it becomes hard. Thus in the case of the red beds under consideration, there appears to be no clear-cut evidence as to whether the contortion of the beds was contemporaneous with deposition or took place at some later time before their consolidation.

As a result of his experiments, Rettger concluded that "practically all 'intraformational corrugated rocks' are produced either by differential movement or by subaqueous slump." Apparently these two processes are so similar and so frequently overlap that they do not give rise to many distinctive features. Most authors have ascribed contorted zones to slump, and Rettger has demonstrated by experiment¹²⁶ that slumping, followed by slight erosion and subsequent deposition, may produce a contorted zone enclosed above and below by horizontal beds; nevertheless the effects of movements caused by rotational forces should not be overlooked in this connection. Despite the possibility that the contorted beds in the Toroweap formation might be due to differential movement, the writer favors the idea of slumping for the following reasons: (1) the folding is very irregular and the angles of dip in the folds are not constant; (2) the bedding is extremely variable in thickness and in many places difficult to trace laterally; (3) many intraformational contorted zones are beveled across the top.

If the writer is correct in interpreting the gnarly layers among the red beds of the Toroweap as due to subaqueous slumping, the question then arises as to its cause. The possibilities, according to Twenhofel,¹²⁷ are steepness of slope of deposition, excessive local deposition, removal of support through erosion of adjacent deposits, and removal of support through

¹²³ A. A. Baker, C. H. Dane, and J. B. Reeside Jr., *Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico and Colorado*, U. S. Geol. Surv. Prof. Paper 183, p. 54, pls. 16*c*, 18*a*, 1936.

¹²⁴ R. E. Rettger, *Experiments on soft-rock deformation*, Bull. Amer. Assoc. Petrol. Geol., vol. 19, no. 2, p. 272, 1935.

¹²⁵ F. H. Lahee, *Field geology*, 3d ed. (New York: McGraw-Hill Book Co.), p. 78, 1931.

¹²⁶ R. E. Rettger, *op. cit.*, p. 279.

¹²⁷ W. H. Twenhofel, *Treatise on sedimentation* (Baltimore: Williams & Wilkins Co.), p. 522, 1926.

withdrawal of water. The extreme irregularity of boundaries, the closely associated "breccias," and the general inconsistency of beds (figure 31) suggest that any or all of the above factors may have influenced the development of the gnarly character, but the prime factor involved was doubtless a

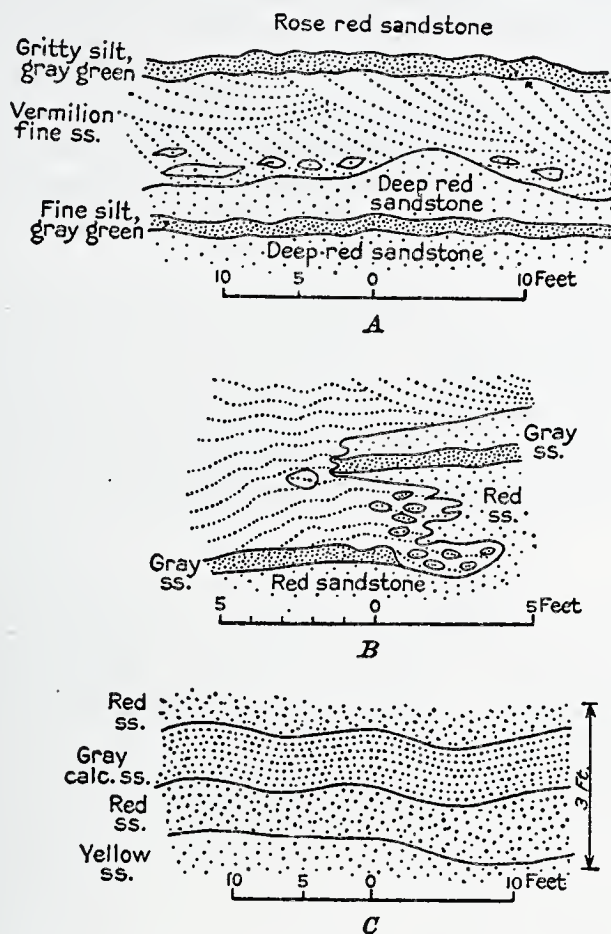


FIG. 31. A. Red beds near Kaibab Trail showing complex character due to gnarly beds, breccia, and cross-lamination
 B. Red beds near Kaibab Trail which illustrate pre-consolidation faulting and brecciation; also cross-lamination and gnarly bedding
 C. Red beds near Kaibab Trail showing gnarly bedding

well-saturated condition of the sediments. Experiments by Rettger¹²⁸ have shown that the relative waviness or sharpness of a structure varies in direct ratio to the degree of saturation or lack of saturation of the sediments.

Primary Origin of Color

The origin of red beds is a subject that has been discussed by many geologists and one that has given rise to many controversies. Whether the coloring is primary or secondary, whether the red beds are of continental or marine origin, and, lastly, what type of climate is to be inferred from red beds, are problems that may yield a different answer for each deposit.

¹²⁸ R. E. Rettger, *op. cit.*, p. 286.

At present there seems to be rather general agreement that in the Permian red beds of western America, at least, the color is primary and was produced by the deposition of ferric oxide as such. As evidence of this, Baker¹²⁹ has pointed out that "the examination of samples from deep borings in the 'red beds' of Texas by Dr. J. A. Udden has demonstrated the persistence of the red color in depth." Case,¹³⁰ in speaking of the red clays of Texas, has suggested that the ferric oxide could not be due to dehydration or decarbonation after deposition of the beds because (1) the color is uniform throughout, (2) the density of the clays and lack of filled veins are inconsistent with changes which involve decided increase in volume, and (3) the red color transgresses into limestones and sandstones with marine fossils.

In the red siltstones and fine sandstones of the Toroweap and Kaibab formations, the hypothesis of primary origin, accepted for the Permian red beds in general, seems to apply. So far as can be determined by exposures, the red color is uniform throughout, and logs of wells drilled at Williams and Coconino Siding by the Santa Fe Railway Company¹³¹ indicate that the red color appears far beneath the surface.

Place of Deposition

Red beds have been supposed by numerous geologists to typify continental deposition. Many unquestionably do. Barrell speaks of them as having formed "typically as fluvial and pluvial deposits upon the land, though to a limited extent as fluviatile sediments coming to rest upon the bottom of a shallow sea."¹³² On the other hand, several recent writers have brought forth rather convincing evidence to show that certain red-bed deposits, at least, are probably not continental but marine. Branson and Mehl¹³³ note that, where marine fossils are scarce in red beds, they constitute a depauperate fauna, thus indicating that the deposits were laid down under marine conditions unfavorable to normal sea life. Likewise, a specialized marine environment has been postulated by Thomas¹³⁴ for certain Permian red beds in Wyoming because of their unfossiliferous nature, their lack of mud cracks or raindrop impressions, and the notable absence in them of lenticular beds, marked textural changes, channeling, and cross-lamination. Thus apparently red-bed deposits may represent either marine or continental origin.

¹²⁹ C. L. Baker, *Origin of red beds*, Univ. Texas Bull. 29, p. 3, 1916.

¹³⁰ E. C. Case, *The Permo-Carboniferous red beds of North America and their vertebrate fauna*, Carnegie Inst. Wash. Pub. No. 207, p. 43, 1915.

¹³¹ Logs kindly furnished by Mr. G. L. Davenport, assistant engineer, A. T. & S. F. Railway Co., Los Angeles.

¹³² Joseph Barrell, *Relation between climate and terrestrial deposits*, Jour. Geol., vol. 16, p. 292, 1908.

¹³³ E. B. Branson and M. G. Mehl, *Triassic amphibians from the Rocky Mountain region*, Univ. Missouri Studies, vol. 4, no. 2, p. 21, 1929.

¹³⁴ Horace D. Thomas, *Phosphoria and Dinwoody tongues in lower Chugwater of central and southeastern Wyoming*, Bull. Amer. Assoc. Petrol. Geol., vol. 18, no. 12, p. 1692, 1934.

The origin of the red beds of the Toroweap and Kaibab formations is a difficult problem. Unlike the underlying red beds of the Permian Hermit shale and Supai formation, which contain fern impressions and the tracks of vertebrate animals, they are barren of fossils. Nor do they show alternate units of flat-bedded shales and cross-laminated sandstones, with abundant mud cracks, raindrop pits, and rippled surfaces such as are so common in these lower formations. The red beds in the Toroweap and Kaibab formations are remarkable for their lack of definite bedding and, in many places, for their gnarly character. Except for breccias, travertines at numerous horizons, and associated deposits of gypsum and impure limestone in some areas, they have few distinctive features.

From the scanty evidence at hand, the writer believes that the red beds of the Toroweap and Kaibab formations were formed under conditions that were neither strictly continental nor strictly marine, but which involved landlocked basins bordering the sea. A possible exception to this is represented by the basal red beds of the Toroweap formation (γ member), which are more evenly and definitely bedded than those above and which everywhere rest upon a remarkably flat upper surface of the Coconino sandstone—a feature that can be explained only as the result of the beveling of unconsolidated sands by an encroaching sea (see page 15).

The extensive saline deposits that are associated with the red beds in the Toroweap and Kaibab formations testify to the fact that deposition took place in basins isolated, at least intermittently, from the main body of marine waters. Travertine deposits confirm the suggestion, and the numerous local “breccias” or intraformational conglomerates are features that are to be expected in such an environment of periodic floodings and desiccation. Unfortunately it does not appear possible to show whether these “breccias” are the results of erosion above water or of shifting submarine currents. As the evaporation deposits among the red beds all are found in the seaward portions of the basins, it appears certain that the red beds themselves were not deposited in the open sea.

Climatic Indications

Inferences regarding climate that have been drawn from red-bed deposits are scattered through a voluminous literature. Barrell, one of the greatest students of this subject, long ago concluded that “the origin of such sediment is most favored by climates which are either constantly cool or constantly wet or constantly dry.”¹³⁵ He pointed out that the alternation of seasons of dryness with those of flood allows hydration and also oxidation of ferruginous material, and that these processes not only decompose the original iron minerals, but also completely remove all traces of carbon. Writing on this subject a decade later, however, Case states that “it now seems to be fairly well accepted that such deposits . . . are the

¹³⁵ Joseph Barrell, *Relation between climate and terrestrial deposits*, Jour. Geol., vol. 16, p. 292, 1908.

result of a climate of moderate rainfall occurring in rainy seasons alternating with dry seasons.”¹³⁶

Following a survey of regions where red beds are forming today, Baker has contributed interesting data concerning their significance. He states that “it is an undisputable fact that red, residual soils, the source of Red-bed sediments, are formed only in warm, moist climates, practically never in arctic, or truly desert, climates. Such soils are formed in uplands where there is fairly good surface drainage, not in bogs, ponds or swamps. Warm, moist climates practically everywhere are characterized by alternations of moister and drier periods.”¹³⁷

Since red beds in the Kaibab and Toroweap formations, as in many other parts of western America, are associated with extensive gypsum deposits, it seems clear that they were deposited under conditions of semi-aridity or aridity in basins where evaporation was extreme. The logical explanation for the red coloring in these formations, therefore, is found in the theory advanced by Baker that such deposits “were derived from old, residual soils of moist, warm climates, transported and deposited without change of color in the arid basins of the late Permian.”¹³⁸ He also calls attention to the fact that “fine, red sediments of the texture of silts can be transported hundreds of miles by streams without losing their red color.” This theory has been applied by Thomas¹³⁹ in explaining the origin of the red beds of the Phosphoria formation in Wyoming, and the writer believes it is equally applicable to those of the Kaibab and Toroweap formations.

Comparison with Colorado Delta Deposits

In a search for basins of recent deposition where conditions are comparable to those represented by the Kaibab and Toroweap formations, the following features have been considered: (1) extreme flatness of region for many miles in all directions; (2) a climate that is semiarid or arid; (3) sediments including a combination of marine deposits, sand dunes, river silts and sands, and playa deposits. In North America probably the nearest approach to these conditions is found at the mouth of the Colorado River in Mexico. In the Old World perhaps an even closer counterpart exists near the mouth of the Nile.

Certain fundamental differences exist between the present area of deposition at the mouth of the Colorado and the former basin of Permian deposition in northern Arizona; nevertheless, many features are similar, especially in the river-borne sediments, so a comparison of these environments is pertinent. The river deposits of the two basins appear to be

¹³⁶ E. C. Case, *The environment of vertebrate life in the late Paleozoic in North America: a paleogeographic study*, Carnegie Inst. Wash. Pub. No. 283, p. 247, 1919.

¹³⁷ C. L. Baker, *Origin of red beds*, Univ. Texas Bull. 29, p. 3, 1916. See also C. W. Tomlinson, *The origin of the red beds*, Jour. Geol., vol. 24, pp. 250-253, 1916.

¹³⁸ *Ibid.*

¹³⁹ H. D. Thomas, *Phosphoria and Dinwoody tongues in lower Chugwater of central and southeastern Wyoming*, Bull. Amer. Assoc. Petrol. Geol., vol. 18, no. 12, p. 1693, 1934.

similar in general texture and character but to differ in color. The bordering dune deposits in all probability are similar; likewise the saline residuals, though in the Colorado basin these apparently are formed in smaller, landlocked basins and therefore are far less extensive than those of the Arizona Permian. Marine deposits undoubtedly differ greatly in the two basins, since from the Colorado delta the sea floor drops off 48 feet to the mile for 100 miles according to Sykes,¹⁴⁰ while in the Kaibab and Toroweap seas the bottom slope must have been excessively slight over vast distances, judging from the persistence in character and thickness of marine beds over a wide area.

The writer does not wish it inferred that he considers the red beds of the Toroweap and Kaibab formations identical in origin with the silts and sands forming the continental portion of the present Colorado River delta. Such an assumption would be unwarranted especially in view of the fact that it is not yet known exactly under what conditions the Permian red beds were deposited. On the other hand, it seems altogether probable that, in the Permian basin as in the Colorado delta, such deposits were introduced by large rivers flowing over flat terrain and deposited under conditions of aridity. The differences in color, therefore, would appear to be the result of differences at the sources from which the sediments were derived and in this sense are simply inherited features in the basins of deposition.

If the sediments carried by the Colorado River to its mouth were, in general, lacking in color, the explanation given above would be adequate. As a matter of fact this river in normal stages is red-brown but varies to vivid red and various shades of brown or dark gray. Why, therefore, are red beds not forming? According to Sykes, "the distinctive color of the Colorado water is imparted to it almost entirely by the fine argillaceous component in the suspended load."¹⁴¹ It should be added that any ferric oxides and hydroxides present are also in suspension with the clays. Sykes points out that, following deposition and dehydration in places where there are still moving waters and air currents removing much of the finer material, decomposition of organic matter takes effect on ferric oxides, and true sun bleaching influences vegetable matter, so the surface color is everywhere light. Exceptions to this, where dark colors (reds, browns, etc.) remain and extend through the mass, are found in situations in which the water has had an opportunity to deposit the finer particles of the suspended load quietly, through evaporation or the gradual draining away of lagoons or backwaters, after coarser material has settled out.

The evidence given above seems to indicate that the dark sediments (those retaining the color seen in the suspended load of the Colorado River) are confined to such deposits as result from quiet settling and are absent from those forming under current action. It therefore appears probable

¹⁴⁰ Godfrey Sykes, *The Colorado delta*, Carnegie Inst. Wash. Pub. No. 460, p. 155, 1937.

¹⁴¹ *Ibid.*, p. 133.

that the red beds of the Toroweap and Kaibab formations were deposited in settling pools free from currents. In support of this theory is (1) their intimate relationship to the gypsum beds, which are playa deposits, and (2) their general lack of cross-lamination, especially of the intricate patterns so characteristic of the current-deposited portions of the Colorado delta. Furthermore, these same red beds when traced eastward from Grand Canyon to the Little Colorado area gradually lose both red color and mud content and at the same time become much cross-laminated (see table 11, page 104).

An additional factor which apparently is necessary for the retention of red color in sediments is an absence of any reducing agent. Rivers of the southern Piedmont carry enormous volumes of red silt into the Atlantic, but deposit no red sediment because disseminated organic matter reduces the ferric oxide and destroys the color. Thus, an arid climate and a basin containing highly saline waters, such as those in which gypsum is deposited, would be very unfavorable to the existence of organic matter and suitable for the survival of red color in sediments. Such conditions are suggested by the red beds of the Toroweap-Kaibab formations.

In marked contrast with the uniformly fine texture of sediments in the Colorado River settling basins is the large percentage of sand-size particles included with the silts and muds of the Permian red beds in *eastern* facies. This feature suggests that all the conditions of deposition were not the same in these basins.

Concerning the matter of texture as related to settling basins, it is interesting to note some results of studies made by Sykes. "The 200 mesh sieve has been commonly accepted as a somewhat arbitrary division between the tractional and suspended loads. . . . accepting [this] as correct, particles which would be retained thereon (very fine sand and above) may be considered as restricted in distribution to channels and other areas reached by *running* water moving with some velocity; while below that critical size (silt and mud) they will be freely distributed by water which merely *flows* in the manner of a general inundation or sheet flood." Biglow¹⁴² has shown that deposits of this latter classification are being laid down at the rate of 5 inches per year from evaporation alone in some modern arid basins.

Mechanical analysis of thirty samples of sediment taken by Sykes from mid-channel bars and shoals at the upper portion of the Colorado River delta are given in table 12. Readily apparent is a marked textural similarity to red beds of the Toroweap and Kaibab formations but a definite contrast with the suspended loads of the Colorado River flood plains. Thus it would seem probable that the sediments of the Permian red beds were introduced into pools or basins by streams with slight currents (greater toward east) but were deposited by settling in quiet waters.

¹⁴² F. H. Biglow, *Studies on the rate of evaporation at Reno, Nevada, and in the Salton Sink*, Nat. Geog. Mag., vol. 19, pp. 20-28, January 1908.

TABLE 12. RESULTS OF MECHANICAL ANALYSES OF SEDIMENTS FROM UPPER PORTION OF COLORADO RIVER DELTA (AFTER SYKES)

Average of group	Retained on 60 mesh	Retained on 100 mesh	Retained on 120 mesh	Retained on 200 mesh	Retained on 300 mesh	Passing 300 mesh
	%	%	%	%	%	%
A.....	4.00	12.81	38.26	29.00	6.53	9.38
B.....	9.15	13.46	40.86	19.55	8.06	5.88
C.....	5.36	11.75	39.96	22.46	12.96	7.46
D.....	6.23	24.83	39.00	15.85	8.43	5.61
E.....	7.75	19.98	32.31	16.21	13.00	10.75
Average.....	6.49	16.56	38.07	20.61	9.79	7.81

Summary

A summary of the writer's conclusions regarding the probable origin of the Toroweap and Kaibab red beds is (1) that the material was derived from a distant region toward the east or northeast having a climate favorable for development of red soil; (2) that the fine sands and muds were brought into the eastern portions of basins of deposition by currents of sufficient strength to move tractional loads as indicated by the texture of the red beds; (3) that the deposits were laid down by more or less continuous settling in quiet pools as indicated by lack of cross-lamination, by retention of fine silts including the ferric oxide pigment, and by association with playa deposits such as gypsum; and (4) that owing to aridity organic matter was lacking or was present in proportions too small to reduce the ferric pigment and thus destroy the red color. The gnarly character of many beds in the eastern facies is attributed to slumping in subaqueous beds, and the transition eastward into non-red, cross-laminated beds is interpreted as the result of greater water agitation by currents in that direction. Similarly, the change from sand to mud deposits westward suggests a reduced amount of water movement there.

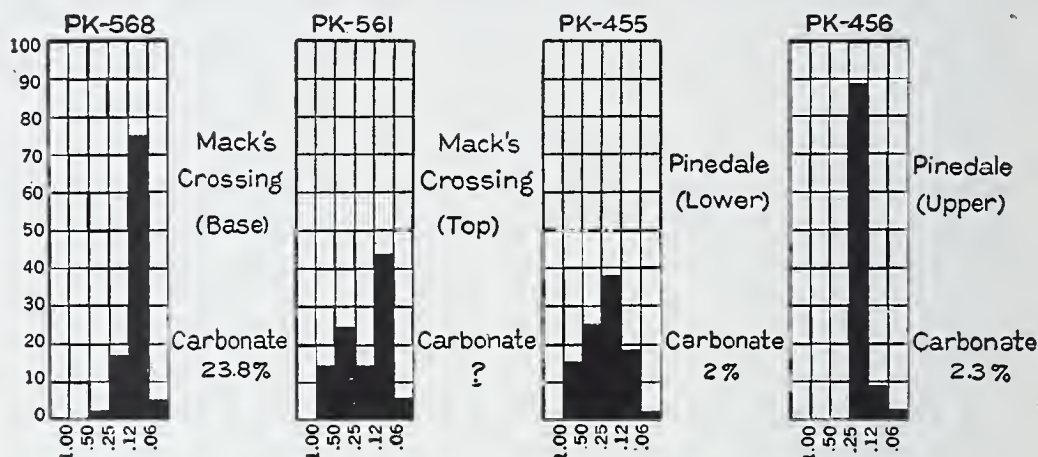
LIGHT-COLORED SANDSTONES

Developed partly under shore and near-shore conditions, the Kaibab and Toroweap contain many units of sandstone occurring both as lateral and vertical transitions and as abrupt changes from the marine limestones. Inasmuch as several distinct environments are represented by these sandstones, the more important types are described and discussed individually. These are as follows: (1) yellow to brown, massive sandstone constituting a near-shore facies of the Kaibab formation deposited during the maximum advance of the sea; (2) chocolate brown, thin-bedded sandstone which is found locally near the base and elsewhere in the upper part of the Kaibab, and was developed after the retreat of the sea; (3) gray, calcareous sandstone or sandy limestone, much cross-laminated, which is found near the top in the eastern part of the Kaibab formation and marks the early stages of the retreat of the sea; (4) white, cross-laminated sandstones of the eastern phase of the Toroweap formation; (5) white, cross-laminated sand-

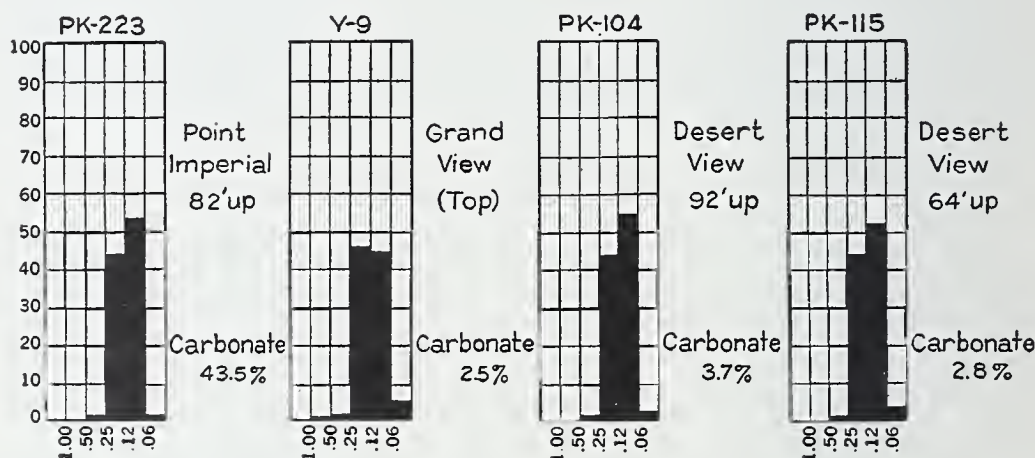
stones of Coconino type in shore phases of the Toroweap and Kaibab formations; (6) gnarly-bedded, light-colored sandstones of the eastern phase of the Toroweap formation.

Yellow to Brown Massive Sandstone of Kaibab Formation

During deposition of the Kaibab formation, a sand facies was developed along portions of the sea margins at the time when this sea reached



A



B

FIG. 32. A. Thin, flat-bedded, brown sandstones of α member, Kaibab formation
B. Massive, yellow sandstones of β member, Kaibab formation

its maximum advance. The facies (no. 3 of β member) appears today as sandstone in conspicuous cliffs forming the walls of eastern Grand Canyon, notably below Desert View Point and Point Imperial. The sandstone weathers gray or reddish brown but on fresh exposures is usually a pale

yellow, white, or rufous. For areal distribution reference should be made to figure 22.

The general character of this sandstone is apparent upon examination of the four histograms shown in figure 32B illustrating the results of mechanical analyses. The marked uniformity of grain size is striking. There appears to be very little silt or mud, yet practically no sand above fine grade.¹⁴³ The amount of calcium carbonate present is another important feature. Although some beds show a high content, as illustrated by sample PK-223, a majority show very little. Through increase in calcium carbonate this sandstone grades westward into sandy limestone, and this in turn grades into crystalline limestone still farther to the west.

The general character of the environment represented by the yellow to brown, massive sandstone of the Kaibab formation is apparent. The fact that this sandstone contains abundant molds of mollusks throughout and that its beds are continuous with those of limestone farther west tends to confirm the view, earlier advanced, that this is a near-shore facies. The unique fossil assemblage (plate 15) may be accounted for by the sandy character of the bottom, although other factors perhaps also had an influence. The massiveness of the beds suggests uniform and essentially continuous settling conditions under which the sand grains were deposited, and the abundance of clastic material indicates the proximity to a broad sandy terrain. Uniformity of grain may be due entirely to derivation from a source in which grains are well sorted or it may be influenced by the sorting power of the transporting agent, therefore the sand might have been delivered to the sea at this point by either water or wind.

Brown, Thin-bedded Sandstones of Kaibab Formation

Flat-bedded, slabby, brown (some white) sandstones, in beds usually ranging in thickness from 1 to 6 inches, are common in various parts of the α member (time of retreating sea) of the Kaibab formation. They are found from the vicinity of Grand Canyon south and east over the Mogollon Plateau. Although usually near the base of the member, some also appear at higher horizons interbedded with thin-bedded, magnesian limestones or other deposits of a residual sea. On their surfaces have been found the tracks of trilobites and the trails of annelid worms (plate 40).

Mechanical analyses of typical sandstones of this type are illustrated by the four histograms of figure 32A. These show that in some examples

¹⁴³ Terminology involving grain size is according to C. K. Wentworth, Univ. Iowa Studies, vol. 11, no. 11, p. 24, 1926. The principal grades referred to in this paper are as follows:

Coarse sand grain	0.5 -1	mm.
Medium sand grain	0.25 -0.5	mm.
Fine sand grain	0.125-0.25	mm.
Very fine sand grain	0.062-0.125	mm.
Silt particle	0.031-0.015	mm.
Clay (mud) particle	Under 0.015	mm.

the clastic grains are poorly sorted. Essentially all grains are quartz, and, especially in the coarser ones, the grains are well rounded.

Regarding the origin of this sandstone, several features seem to be significant. The local character of any particular group of beds and its presence between impure limestones and other deposits of a retreating sea suggest deposition in landlocked basins or small pools. The presence of tracks and trails indicates shallowness of the water. The flatness of the beds and proximity to limestones point toward quiet water. Probably, also, the thinness of beds reflects the environment. Apparently they were formed at a time when deposition was frequently interrupted.

Cross-laminated Calcareous Sandstone of Kaibab Formation

Certain thick, conspicuously cross-laminated beds of calcareous sandstone that grade into sandy limestone had their origin during the waning stages of the Kaibab sea, that is, just before its retreat from the eastern Grand Canyon area. Such beds are found along the Little Colorado Canyon in at least two horizons and near Lees Ferry, where they form the top of the Permian section. The cross-lamination and the hard ledge-forming character of these beds give them prominence wherever found.

A discussion of this calcareous sandstone requires an understanding of its composition and texture. Reference to the three histograms in figure 33A is suggested for this purpose. Numbers X-1 and A-7 illustrate typical samples in which the texture shows sorting of the clastics into two grades, one coarse and the other fine to very fine. Such a sample might also have been selected from the locality represented by K-1, but the one used shows that the "double maximum" does not occur throughout the bed in any place. The coarse grains, wherever present, are well-rounded quartz, much frosted and pitted, whereas the more abundant but less conspicuous fine grains are, for the most part, subangular.

The cross-lamination of the Kaibab calcareous sandstones appears only on the weathered surface. On fresh, non-etched surfaces, its presence can seldom be detected and samples look more like normal limestone than sandstone. Reference to the varied and in places rather low percentage of calcium carbonate, as indicated by analyses, and to the dominance of elastic sediments seen in thin-sections, however, leaves little doubt of the desirability of classing this type as a sandstone.

The present nomenclature and classification of types of cross-bedding are inadequate satisfactorily to describe the varieties found in the Kaibab calcareous sandstone, but illustrations serve to give some idea of its character. In plate 31c may be seen its location immediately above chert-bearing limestone near Lees Ferry. In plate 31a appears a not uncommon type of recurring cross-lamination which is similar to bedding obtained during experimentation in delta building by Nevin and Trainer.¹⁴⁴ They devel-

¹⁴⁴ C. M. Nevin and D. W. Trainer Jr., *Laboratory study in delta building*, Bull. Geol. Soc. Amer., vol. 38, p. 457, 1927.

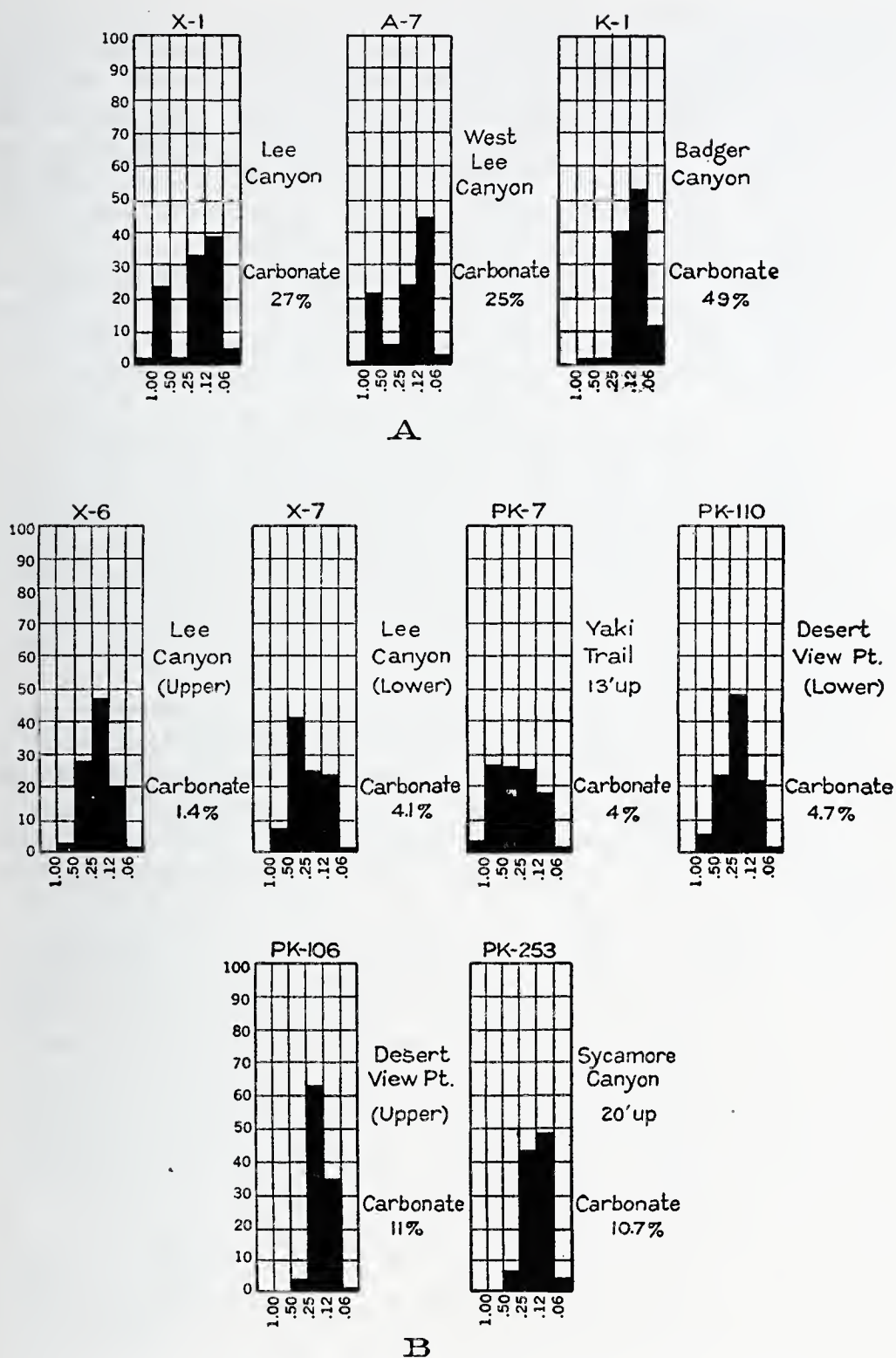


FIG. 33. A. Cross-laminated, calcareous sandstone, Kaibab β , top member
 B. White, cross-laminated sandstone, Toroweap member

oped nearly identical structures as a result of abrupt rises in water level. A third feature is illustrated in plate 31*d*. Here the soft sediments were apparently caused to slump by an object falling on the surface. This probably gives some clue as to the shallowness of the water. By experimentation, Rettger found that "most favorable conditions for penetration occurred when freshly deposited sands were covered with not more than one inch of water."¹⁴⁵ Greater depths, he states, retard the fall of the object, and less water results in firmer packing of sediments.

Briefly stated, the environment represented by the calcareous sandstones of the Kaibab formation (facies 4 of β member) is probably that of very shallow water, affected by considerable current movement, at a time when the open sea began to retreat from the area of its maximum advance.

White, Cross-laminated Sandstones of Toroweap Formation

Prominent in the eastern phase of the Toroweap formation are beds of white sandstone consistently made up of uniformly sloping laminae which everywhere have level tops and bottoms. Not only do these beds make up a large part of the eastern phase, but also they extend westward for many miles as thin tongues in the red beds of α member, and, in the opposite direction, they are recognizable among the truncated wedges of white, Coconino-like sandstone. See plate 32.

The grains in most of these white sandstones are rather poorly sorted (see figure 33B). They range from medium or even coarse sand down to very fine, but contain essentially no silt or mud, which, together with the clear texture of the quartz particles, no doubt explains the usual whiteness of the rock. Calcium carbonate content has been found low wherever examined, and cement of other types is also scarce, therefore the rock is friable.

The mechanics of the cross-lamination in this type of sandstone are simple. Figure 34 illustrates its nature. Each bed was built forward across a level surface by a current that deposited rather uniform sloping, flat sheets of sand. One layer after another was deposited in identical manner, until finally the characteristic pattern resulted. The level upper surface of the bed may then have been formed by a planation of the tops of the laminations just developed, but in all probability it was largely constructional, the result of a constant water level and current velocity during deposition, causing concentration of sand on the fore-set rather than the top-set surfaces and keeping the top swept clean to a definite level. In pattern, the "torrential cross-bedding" of Lahee¹⁴⁶ is similar but details such as the short, straight, rather than long, tangential bedding planes, also the lack of top-set beds, indicate a fundamental difference in the Toroweap deposits.

¹⁴⁵ R. E. Rettger, *Experiments on soft-rock deformation*, Bull. Amer. Assoc. Petrol. Geol., vol. 19, no. 2, p. 275, 1935.

¹⁴⁶ F. H. Lahee, *Field geology*, 2d ed. (New York: McGraw-Hill Book Co.), p. 80, 1923.

The recognition of this type of cross-lamination and its distinction from the truncated-wedge type so characteristic of the otherwise similar Coconino sandstone makes possible the differentiation of sandstone units in certain questionable areas. In the walls of Oak Creek Canyon, for example, the

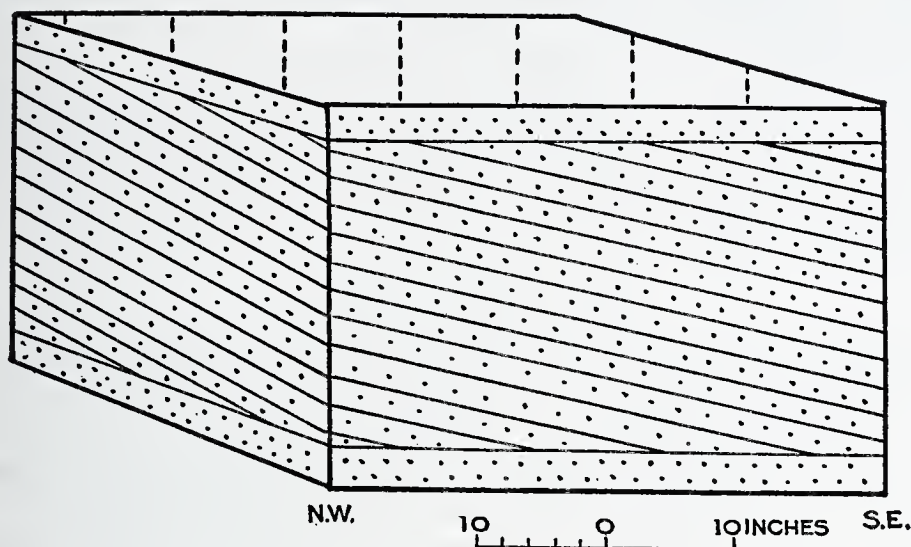


FIG. 34. Typical cross-lamination in eastern phase of Toroweap formation. Sketch from white sandstone tongue below El Tovar.

upper and smaller white sandstone cliff, which is separated from the underlying larger one by a ledge, contains cross-lamination mostly of this type. In the lower cliff, however, the typical Coconino variety is present. Farther east in Walnut Canyon, in the sandstone formerly assumed to be Coconino, cross-lamination of both types is recognized, thus indicating correlation with the eastern phase of the Toroweap formation but a partial change to (or an upward extension of) Coconino conditions. It is believed that wind-deposited and water-deposited sands are found together at this locality.

Coconino-like Sandstones

In the preceding discussion of a cross-laminated sandstone characteristic of the eastern phase of the Toroweap formation, mention was made of its occurrence in certain localities together with sandstone having Coconino-like cross-lamination. This mingling of types undoubtedly is the result of a mingling of environments. Since the truncated-wedge variety typical of the Coconino sandstone is thought ¹⁴⁷ to represent æolian deposition, it is probable that on the eastern borders of the Toroweap formation a dune environment is represented stratigraphically higher than the Coconino sandstone and associated with deposits of a water-laid type.

Recurrence of Coconino-like cross-lamination—hence dune environment—is found still higher stratigraphically in Permian rocks to the south and

¹⁴⁷ Edwin D. McKee, *The Coconino sandstone—its history and origin*, Carnegie Inst. Wash. Pub. No. 440, VII, 1934.

east. Plate 33a shows a white, cross-laminated sandstone, thought to be of this type, near Long Valley, Arizona, in the α member of the Kaibab formation. Farther east near Pinedale, a 60-foot outcrop of sandstone which undoubtedly represents a Coconino-like environment occurs above a fossil-bearing, gray limestone probably also belonging to the α member of the Kaibab formation.

In conclusion, the writer wishes to emphasize the principle that, in types of sediments just as in assemblages of fossils, resemblance indicates similar environment but not necessarily contemporaneity. Extreme care must be taken, therefore, in correlating the various lithologic units that occur, usually in poor exposures, along the borders of the Kaibab and Toroweap formations.

Gnarly-bedded Sandstone

Among the light-colored sandstones that constitute the eastern phase of the Toroweap formation, many beds show an irregular, gnarly character. Most of them are fairly thick and massive, as shown in plate 6d, but in a few places the same type of gnarly structure has been developed in quartzitic beds, only a few inches thick, located among white sandstones as seen in plate 5d. The prevailing massive type of bed referred to above is largely structureless where seen in Grand Canyon sections, but farther east these beds contain intricate cross-lamination patterns.

Among the Permian rocks of northern Arizona the light-colored gnarly sandstones appear to be exclusively a feature of the eastern phase of the Toroweap, where they make up most of the upper two-thirds of the formation. They are particularly well exposed in the walls of Badger Canyon near the head of the Marble Gorge and in Straight and Lee Canyons to the north and east, respectively, of Cedar Mountain near Grand Canyon.

The light-colored, gnarly beds of sandstone described above appear to be definitely related to certain of the Toroweap red beds (α member) which show a similar irregular bedding. Evidence of this is found in transitions from a pure white to a deep red rock. Briefly stated, from west to east the following types of sediments appear in the same members: (1) gnarly, massive red beds with gypsum deposits and associated chemical limestone beds; (2) gnarly, structureless red beds of massive, irregular character; (3) gnarly beds of light-colored sandstone with massive irregular character; (4) gnarly, thick beds of light-colored sandstone displaying throughout intricate patterns of scour-and-fill cross-lamination on a small scale.

The gnarly beds in the eastern phase of the Toroweap formation undoubtedly owe their peculiar irregular character to the same factors that caused such irregularities in the stratigraphically equivalent red beds. They represent a form of soft rock deformation (see pages 105–107). As in the case of the red-bed deposits, it is believed that in the light-colored sediments, gnarly bedding was developed by slumping while in a saturated condition. Further evidence is supplied by the wavy, indefinite character

of some of the cross-laminations in the gnarly beds and also by confused mixtures of massive, featureless sandstone and sandstone containing well-defined cross-lamination patterns.

In the Toroweap gnarly beds change in color from deep red in the west to white in the east appears to be the result of loss of ferruginous silt and

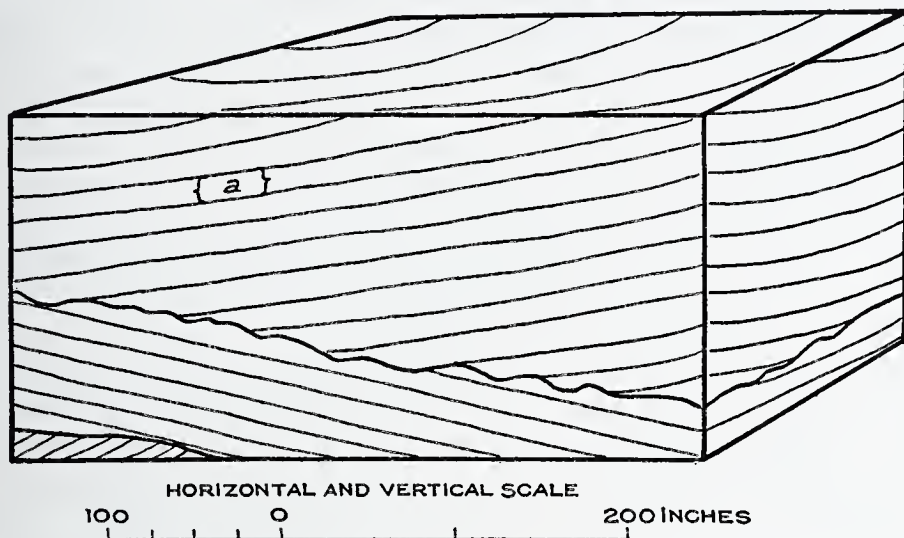


FIG. 35. Typical sample of penecontemporaneous erosion surfaces and sloping deposits in sandstone of Toroweap α , Lee Canyon. Block diagram from 3-dimension field sketch.

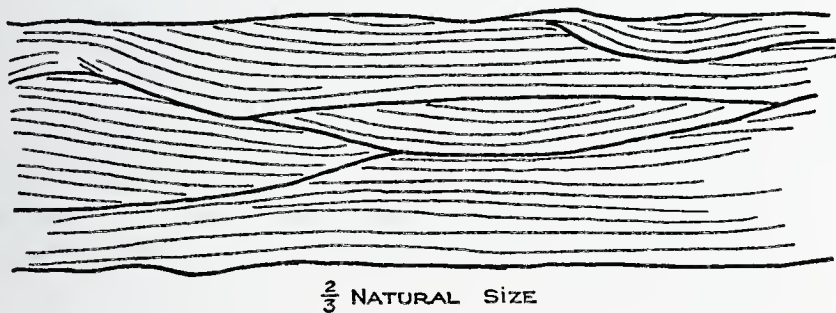


FIG. 35a. Detail view of small-scale scour-and-fill development within sloping beds illustrated by figure 35

mud content, as illustrated by comparison of the histograms of four samples from Lee Canyon which had little color (figure 27) with the sixteen samples of typical red beds from farther west (figures 26 and 27). In further support of this view is the fact that the light-colored sandstones were deposited by active currents as indicated by their intricate cross-lamination patterns, while the red beds apparently were deposited in quiet water.

GYPSUM

Description

Gypsum is common in certain parts of the Kaibab and Toroweap formations. In exposures of the α member of the Toroweap from Havasu Canyon

westward and northward, it is interbedded with impure, thin-bedded limestones and red beds. A similar association in the α member of the Kaibab formation north and west of Toroweap Valley has caused that unit to be termed the "Harrisburg gypsiferous member."¹⁴⁸ Gypsum is also present in the γ member of the Toroweap formation on the Shivwits Plateau and farther north near the Arizona-Utah boundary.

The Toroweap-Kaibab gypsum deposits have been examined in detail by the writer in only two localities, the vicinity of Havasu Canyon, Arizona, and north of Wolf Hole near the Arizona-Utah boundary. Judging from general appearances in other localities and at other horizons, however, it seems probable that their history is essentially the same throughout these formations. Unfortunately, in practically every place where the gypsum deposits are found, exposures are poor because the weak character of these beds and also of the associated red beds causes the development of slopes which are usually covered with talus.

The gypsum deposits of the α member, Toroweap formation, where examined at Hilltop near Havasu Canyon, show marked lateral variation and lensing. In comparatively short distances the beds vary from dense, hard, white material to a coarse, soft, massive, sacchroidal type. Detailed measured sections of such members have little comparative value. Typical series of beds containing gypsum deposits, however, are illustrated below:

Locality 1 (read from bottom up)

4. Red bed, fine sandstone; veins of gypsum throughout, no limestone	Feet
3. Rock gypsum, massive beds, folded conformably with underlying limestone; fresh surface shows angular fragments and lenses of gray limestone; weathered surface stained and covered with red sand giving a deceiving appearance	3.00
2. Limestone, gray banded (light and dark), thin-bedded, weathers to smooth blocky surface; bedding irregular and much folded; veins of gypsum, definitely secondary, pass through in all directions, especially vertically	1.00
1. Red bed, fine sandstone, very friable	

Locality 2 (read from bottom up)

6. Sandstone, yellow, very fine-grained	8.00
5. Rock gypsum, impure, very little limestone included in bed	1.25
4. "Breccia" of limestone and gypsum fragments	1.00
3. Limestone, gray, thin-bedded, weathers smooth and blocky	0.25
2. Rock gypsum, impure with thin veins of pure gypsum throughout	1.50
1. Sandstone, yellow, massive, irregular bedding	

A feature of the gypsum beds of the Toroweap formation at Havasu Canyon is the occurrence of "breccias"¹⁴⁹ at various horizons. These are

¹⁴⁸ Term not continued in classification proposed in this paper.

¹⁴⁹ "Breccias" in gypsum deposits have been noted by various geologists. See Ackers, DeChicchis, and Smith, *Hendrick Field, Winkler County, Texas*, Bull. Amer. Assoc. Petrol. Geol., vol. 14, no. 7, p. 929, 1930; also J. A. Allan, *A new deposit of gypsum in the Rocky Mountains, Alberta*, Canadian Inst. Min. and Met., p. 11, 1933.

composed of angular fragments of limestone and gypsum (possibly limestone in gypsum) which the writer believes may best be interpreted as intraformational conglomerates because they are unrelated to structures and are irregular in both lateral and vertical distribution. Similar breccias are also common in the red beds of the α member farther east. These are discussed in detail elsewhere in this chapter under the title "Intraformational Conglomerates."

The character of typical gypsum samples from the Havasu Canyon locality is illustrated in plate 36*b*. The great abundance of quartz sand in certain thin-sections is a striking feature. In hand specimens the sand grains are not conspicuous and a dull white, earthy surface is all that is readily apparent. In samples from red beds immediately above the gypsum beds, clastic grains are cemented with gypsum (plate 36*a*). From this extreme all gradations are found in the ratio of sand to gypsum, some samples showing almost pure gypsum.

Plate 36*c* shows a specimen of gypsum which is relatively free from clastic sand but which contains a limestone fragment. It is not clear whether the narrow tongues of gypsum extending into the limestone in this specimen are due to replacement or are merely the results of filling fractures or openings. In either case, however, it shows clearly that the gypsum is later than the limestone, as might be expected. Further evidence of this and a suggestion that the gypsum is not replacing the limestone is found in several sections that show a "comb structure" in the gypsum that fills cavities in the limestone.

The gypsum beds at Havasu Canyon, which have just been described, are on the eastern margin of the area of evaporation deposits in the α member of the Toroweap formation. For comparison, other gypsum beds were examined at a place 8 miles north of Wolf Hole, Arizona, which is near the geographical center of the area in which gypsum is found in this member. These deposits differ chiefly in being much thicker and uniformly purer. Associated red beds are composed entirely of mud and silt rather than fine sand. The following partial section shows the character of the gypsum beds and their relationship to others:

(Read from bottom up. See plate 35)

	Inches
Erosion surface; top of hill	
7. Gypsum, rock, pure white	Exposed 46
6. Limestone, gray, thin-bedded, impure; weathers smooth and blocky	24
5. Gypsum, rock, pure white	45
4. Limestone, gray, thin-bedded, impure; weathers smooth and blocky	48
3. Red bed, mud and silt, no sand; crumbly, non-bedded; contains veins of secondary gypsum	38
2. Gypsum, rock, pure white	34
1. Red bed, mud and silt, no sand; crumbly, non-bedded; contains veins of secondary gypsum	Exposed 43

Origin

Regarding the origin of gypsum, five principal types have been recognized. These are summarized by Twenhofel as follows: "(1) deposits from springs either through evaporation or freezing; (2) efflorescences on, or just beneath, the surface as the result of deposition from ground water; (3) mechanical deposition by wind and possibly by water; (4) evaporation of lakes and playas and marginal or isolated bodies of the sea; and (5) replacements of other substances."¹⁵⁰ It is not the intention of the writer to discuss in this paper these various types of origin, but rather to point out the environment in which the gypsum beds of the Kaibab and Toroweap formations were developed as indicated by the evidence at hand. In this only the last two methods listed above need be considered.

The gypsum deposits of the Toroweap formation were first examined in 1858 by J. S. Newberry in the vicinity of Havasu Canyon. He concluded that this gypsum was "altogether a secondary product, formed after the deposition of the strata containing it and in great part subsequent to their elevation above the ocean level."¹⁵¹ He further stated that "if a blue or gray calcareous rock, containing large quantities of pyrites, were subjected to the peculiar exposure . . . of the tablelands . . . and permeated age after age by meteoric water carrying carbonic acid and oxygen to the pyrites, the results would be precisely what we now find to have taken place."

In support of his replacement theory, Newberry stated four reasons why he thought the gypsum could not have been the result of "the action of sulphurous water or vapors on coral reefs or other masses of carbonate of lime." Apparently he regarded this as the only alternative hypothesis. His reasons were: first, the extent of the deposits; second, their general and uniform diffusion through the rocks; third, the presence of transverse veins of gypsum; and lastly, the association with red beds, which is incongruous with the idea of coral-reef origin.

In the light of present knowledge concerning the origin of gypsum, it seems rather evident that only the third of Newberry's criteria actually supports his hypothesis of replacement, while the other three criteria support the idea of deposition through evaporation, a theory now widely accepted for most such deposits throughout the world. The veins of gypsum that have been referred to as passing through the red beds and limestones no doubt are due to local secondary development, either replacement or cavity filling; however, these local occurrences give no evidence whatsoever concerning the extensive beds of gypsum. The lack of pyrite throughout the formation, furthermore, is a factor quite opposed to any theory involving widespread replacement of limestone.

A method of forming gypsum which should be considered in connection

¹⁵⁰ W. H. Twenhofel, *Treatise on sedimentation* (Baltimore: Williams & Wilkins Co.), p. 350, 1926.

¹⁵¹ J. S. Newberry, *Report upon the Colorado River of the West, explored in 1857-58 by Lieut. J. C. Ives* (Washington: Government Printing Office), pt. 3, Geological report, p. 64, 1861.

with the deposits in the Toroweap and Kaibab formations is the alteration of anhydrite. Ries¹⁵² states that some geologists believe that much of the gypsum now found was originally anhydrite, but he points out that "if anhydrite represents the original mineral, then its change to gypsum must be accompanied by increase of volume in the mass, and one might expect to find a shattering or deformation of the surrounding beds." Allan¹⁵³ has illustrated highly folded and contorted bands of gypsum from Peace River, Alberta, which he regards as the result of hydration of anhydrite. In the Kaibab and Toroweap formations, no such intense folding of gypsum beds is evident, although a minor amount of shattering is locally common. In such places the fracturing of the gypsum may easily have been caused by structural disturbances, for the associated beds are also contorted. Negative evidence of this type gives no proof of the origin of the deposits, inasmuch as a relatively high original porosity might have taken up an increase in volume; however, the apparent lack of marked increase in volume, together with the general absence of anhydrite in the formation, leads the writer to favor the view that the gypsum beds were deposited originally as such.

Doubtless most gypsum beds, along with other saline residues, have been formed by the evaporation of salt water either in inland seas or in arms of the ocean. Baker¹⁵⁴ has pointed out that three fundamental assumptions are requisite to account satisfactorily for immense volumes of saline residues such as are found in various Permian deposits. These are (1) a total amount of evaporation greater than the total water supply from all sources, (2) a more or less constant long-continued supply of water from the ocean, and (3) a basin of sedimentation whose base sinks sufficiently to allow continuous or repeated deposition.

Probably the extensive gypsum deposits of the Kaibab and Toroweap formations of northern Arizona and southern Utah were formed under conditions comparable to those just postulated. The interstratified character of the gypsum series where limestones, fine sandstones, and siltstones are interbedded with the gypsum strongly suggests this. That no salt was also deposited in the shallow basins or playas indicates either that no chlorides were present in the water, or that, after the sulphate was precipitated, evaporation did not proceed to the saturation point for salt. Apparently the wide interval between the concentration necessary to form gypsum and that required for sodium chloride was too great to be spanned under the prevailing conditions.

Modern Gypsum Deposits

Having discussed the history and origin of gypsum beds in the Permian of Arizona, the writer believes it desirable to compare these with certain

¹⁵² H. Ries, *Economic geology* (New York: John Wiley & Sons), p. 247, 1925.

¹⁵³ J. A. Allan, *Salt and gypsum in Alberta*, Trans. Canadian Inst. Min. and Met., pp. 21-22, 1929.

¹⁵⁴ C. L. Baker, *Non-arid genesis of American red-beds*, Pan Amer. Geologist, vol. 52, p. 351, 1929.

modern deposits which are probably somewhat similar in origin and, therefore, represent comparable environments.

In North America gypsum is being deposited extensively in lagoons that fringe the Gulf of Mexico between Tampico, Mexico, and Corpus Christi, Texas. These lagoons, discussed in detail by Baker,¹⁵⁵ are very shallow and are bordered on the mainland side by low, flat lands that extend inland many miles. They are separated from the Gulf by sand bars over which at rare intervals hurricane winds wash the Gulf waters or, in a few places, narrow and shallow passages permit periodic influx of Gulf waters. The annual rainfall is said to vary from 20 to 36 inches, but there is a relative scarcity of inflowing fresh waters, while strong winds and high temperatures favor evaporation. The water in one lagoon is said to have 2.6 times the average salinity of the Gulf of Mexico and is so concentrated that more than two-thirds of its calcium carbonate has been precipitated.

In the Old World, the Caspian-Aral Basin stands as a classic example of a basin accumulating saline residues. According to Baker, "the Caspian has only a little more than one-third the salinity of the ocean, but the salinity of Karabugas Gulf is 22 times that of the Caspian and eight times that of the ocean. A current continually flows from the Caspian into the Karabugas and there is no compensating return current. This current carries 350,000 tons of salt into the Karabugas daily,"¹⁵⁶ therefore, saline deposits are forming upon its bottom and sides. Baker also states that "much of the salt and gypsum originally present in Caspian water at the time it was cut off from the Black Sea has been deposited on areas now dry land but formerly a part of the Caspian, or is left in the salt lakes and marshes formerly connected with the Caspian."

The two examples just cited of modern basins in which gypsum is being deposited are different in character, yet both have certain fundamental features in common—features which must also have been present in the Arizona Permian basins. While there is little evidence to indicate either the depth of the Permian basins or the nature of their connections with outside waters, the examination of modern areas of gypsum accumulation makes it appear reasonably certain that these ancient basins must have been in a region of great evaporation and that they were continuously or repeatedly replenished with saline waters.

INTRAFORMATIONAL CONGLOMERATES

"Intraformational conglomerate" is defined by Walcott¹⁵⁷ as a conglomerate developed by the breaking up of a partially consolidated bed and the incorporation of the fragments in new strata nearly contemporaneous with the original beds. Sedimentary deposits apparently of this type have been found in various parts of the Toroweap formation.

¹⁵⁵ *Ibid.*, pp. 346–347.

¹⁵⁶ *Ibid.*, p. 348.

¹⁵⁷ C. D. Walcott, *Paleozoic intraformational conglomerates*, Bull. Geol. Soc. Amer., vol. 5, pp. 191–198, 1894.

Noble is the only student of the Toroweap formation who has referred to its intraformational conglomerates. He has described this feature in some detail and has offered suggestions regarding the significance of such deposits. Concerning them he states: "Undoubtedly these brecciated beds are a constant feature of subdivision B [upper red beds of Toroweap formation], for I have seen them at all localities where I have examined the subdivision between Bass Canyon and Red Canyon"¹⁵⁸ in the Grand Canyon. In a later paper Noble refers¹⁵⁹ to the "breccia" as very widespread and persistent, occurring at Kaibab Gulch in Grand Canyon, northwest of the Kaibab Plateau, and around Cataract Canyon, but he points out that it is not everywhere at the same horizon.

The intraformational conglomerates of the Toroweap formation not only are found at various horizons in the upper red-bed series (B member of Noble's Grand Canyon section), but also have been noted by the writer in the lower red beds—beneath the massive limestone and a few feet above the Coconino sandstone—at Grand Wash Canyon. They consist in most places of angular, poorly consolidated fragments of tan and red sandstone (plate 37) and in other localities of gypsum and even of limestone of the chemically precipitated, playa type. The matrix is, for the most part, an irregularly bedded, sandy material, commonly much twisted and gnarled in appearance.

Near the middle of the upper red-bed series in Red Canyon, Noble noted a "breccia" bed 15 feet thick in which sandstone fragments are as large as 4 feet in diameter. At Fossil Mountain the writer found a bed of intraformational conglomerate with associated deposits of travertine (plates 6c and 38) and Noble recorded a similar association at Kaibab Gulch. He also has recorded interbedded lenses of sandy red shale.

Concerning the origin of the "breccias" in the Toroweap formation, Noble points out that in places they resemble coarse conglomerates and are "clearly of detrital origin," but that elsewhere they have the appearance of "rock that has been brecciated in place, either by pressure or by beds caving in and breaking because of some soluble material, perhaps gypsum, being leached out of them." As suggested by Noble, the association with travertine such as is found in Tertiary fresh-water deposits of the California and Nevada deserts of today, the resemblances to conglomerates, the presence of interbedded red shales, the close association with gypsum and other playa deposits, all strongly suggest a nonmarine origin contemporaneous with red-bed deposition, which probably took place in landlocked or nearly landlocked basins of shallow water.

By the process of elimination, it thus becomes practically certain that the "breccias" of the Toroweap formation must be true intraformational deposits. First, the fragments were not formed by the leaching of soluble

¹⁵⁸ L. F. Noble, *A section of the Paleozoic formations of the Grand Canyon at the Bass Trail*, U. S. Geol. Surv. Prof. Paper 131, p. 70, 1922.

¹⁵⁹ L. F. Noble, *A section of the Kaibab limestone in Kaibab Gulch, Utah*, U. S. Geol. Surv. Prof. Paper 150, p. 51, 1928.

materials, such as gypsum, with consequent caving in, for (1) the breccias are found in areas where gypsum is absent and apparently never was present as well as in those containing it; (2) the deposits wedge out laterally; and (3) they are not confined to any particular horizons. Second, they could not have been formed as a result of deformation of the area, i. e. as fault breccias, for (1) in vertical sections, the same types of rock at other horizons are commonly unaffected; and (2) there is usually no evidence of movement in the vicinity. Third, they could not have been formed as normal, basal conglomerates, for (1) the fragments are local and angular in character; (2) the horizons are inconsistent; and (3) the beds show extremely abrupt lateral lensing.

Intraformational conglomerates somewhat similar to those in the Toroweap red-bed series have been recorded from the Embar of Wyoming,¹⁶⁰ another formation composed dominantly of Permian red beds. Thomas believes that the Wyoming "breccias" were formed by the "disruption of previously deposited beds by storm waves"—contemporaneous erosion in highly agitated waters. Apparently this conclusion is based on the association of these intraformational conglomerates with red shales most of which, on the basis of several types of evidence, he considers to have been deposited in a specialized marine environment. By the same process of reasoning, it seems probable that the Toroweap red beds, because of their distribution and association with gypsum and other playa deposits, were formed in or near the shallow water of a desert basin and therefore the intraformational conglomerates within them probably were developed by wave action or through surface erosion by intermittent storms.

Local Conglomerates

A feature of sedimentation in the Kaibab formation is the presence, in the Circle Cliffs area, Utah, of limestone beds containing abundant angular fragments of chert. This has been noted by Gregory and Moore, who state that the "chert-bearing bed is in part a residual deposit, and the chert is clearly of secondary origin [i. e., redeposited after consolidation and breaking up], but its position within the formation beneath massive, evenly stratified limestone shows that it does not represent exposure and disintegration of a part of the Kaibab rocks in post-Kaibab time."¹⁶¹

In two places where the writer measured sections of the Kaibab formation in the Circle Cliffs area, conglomerates not only were well developed, but also were found at more than one horizon within the formation. Four miles south-southwest of the Ohio Oil Company's well, the uppermost bed in the formation is a yellow limestone 23 feet thick, which contains abundant gravels of subangular, white quartz and chert, mostly 0.125 to 0.25

¹⁶⁰ Horace D. Thomas, *Phosphoria and Dinwoody tongues in lower Chugwater of central and southeastern Wyoming*, Bull. Amer. Assoc. Petrol. Geol., vol. 18, no. 12, pp. 1671, 1683, 1695, 1934.

¹⁶¹ H. E. Gregory and R. C. Moore, *The Kaiparowits region*, U. S. Geol. Surv. Prof. Paper 164, p. 40, 1931.

inch in diameter and ranging up to 2 or 3 inches. The pebbles are oriented in all directions and some are well rounded. Thirteen feet of similar limestone beneath is free from chert fragments. Still lower, however, is another yellow limestone bed containing subangular quartz and chert gravels.

In a deep canyon immediately southwest of The Peaks in the Circle Cliffs area, the writer noted pebble-bearing limestones at three horizons in the upper part of the Kaibab formation. In each of these the pebbles are chert and quartz, largely subangular but some rounded as at the locality south-southwest of the oil well. In diameter they are, for the most part, less than 1 inch, but a few measured as much as 2 inches. They are un-oriented and in many places very close together.

The Kaibab conglomerates of the Circle Cliffs area are especially significant for two reasons. First, they are within a formation, yet so far as could be determined are unrelated to any unconformity. Second, they are present in strata made up of fine-grained materials, both elastics and other types, which have been rather uniformly deposited, apparently in quiet water. A possible explanation for the surprising appearance of these coarse sediments associated with thick deposits of fine materials is a diastrophic movement in an adjoining area which suddenly started the breaking-up and distribution of a chert-bearing formation. A change in the drainage system leading into this depositional basin or a climatic change might also be regarded as a possible explanation. The former, however, would probably be related to diastrophism and therefore to the theory suggested. Climatic change seems improbable since it would necessarily be regional in aspect, yet is not reflected elsewhere or in other ways in the formation.

CYCLIC SEDIMENTATION

Major Cycles

The occurrence and the importance of cycles in geologic history have become more and more apparent within recent years and various aspects of the subject have been discussed by numerous geologists. The term "cycle" as applied to repetitions in deposition and erosion of sediments has been given prominence by Weller, Wanless, R. C. Moore, and others through discussions on sedimentation of the Pennsylvanian period. "Cycle" has been defined by Weller as an implication of a "recurrence, repetition, or a return to the starting point"¹⁶² without a time consideration as in regular or measured movements. For the latter he suggests use of the term "rhythm."

In the Pennsylvanian rocks of Illinois, Weller¹⁶³ in 1930 recognized a cyclical repetition of beds consisting of (1) sandstone and sandy shale, (2) underclay, (3) coal, and (4) marine limestones and shales. He concluded that each cycle began with a period of uplift, followed first by ero-

¹⁶² J. Marvin Weller, *Cyclic sedimentation of the Pennsylvanian period and its significance*, Jour. Geol., vol. 38, no. 2, p. 99, 1930.

¹⁶³ *Ibid.*, pp. 97, 102.

sion, then by continental deposition; that this in turn was followed by subsidence and marine deposition. Wanless¹⁶⁴ showed similar typical sequences which he termed "cyclical formations" in a report on western Illinois published the following year. In 1935 Moore, Elias, and Newell¹⁶⁵ illustrated in diagrammatic form a cycle of sedimentation consisting of nine units or "phases" occurring in the Pennsylvanian of Kansas.

In connection with his studies of Pennsylvanian strata in the Midwest, Weller proposed the term *cyclothem* "to designate a series of beds deposited during a single sedimentary cycle."¹⁶⁶ It is, he states, to be ranked as a formation but is less likely to be loosely employed than is that term. Moore not only accepts the word *cyclothem*, but also uses "megacyclothem" to designate "two or more cyclothem of different characters that occur in regular sequence," and "phase" to indicate one of the units that go to make up a cyclothem.

Both the Toroweap and the Kaibab formations are thought by the writer to be true cyclothem, and the members which they include are therefore equivalent to the "phases" of Moore, though they are much thicker. The cycle represented by the transition from red beds and gypsum deposits to marine limestones and back to red beds and gypsum forms a sequence which differs from that of the various Pennsylvanian cyclothem referred to not only in thickness of units but also in number and arrangement of units and in the matter of unconformities. In sequence it appears to be more nearly comparable with the Permian cyclothem of Kansas, whose "phases" go from continental deposits to brackish-water deposits, to marine deposits, then back in reverse order. In the Toroweap formation, the thin-bedded, chemically precipitated limestones at the base and the top of the marine limestone probably also should be considered divisions of the cyclical formation, even though relatively thin. Thus the ideal cyclothem would be:

1. Red beds and gypsum
2. Chemically precipitated limestones
3. Marine limestones with mollusks or brachiopods
2. Chemically precipitated limestones
1. Red beds and gypsum

In the Kaibab formation these units of the cyclothem are not so readily distinguishable as in the Toroweap, but the transition near the top from the marine limestone to brackish-water limestones, to red beds and gypsum, suggests that the general history of sedimentation was somewhat comparable.

In the red beds forming the upper part (α member) of the Toroweap formation, numerous thin beds of limestone are represented, probably as

¹⁶⁴ Harold R. Wanless, *Pennsylvanian section in western Illinois*, Bull. Geol. Soc. Amer., vol. 42, p. 803, 1931.

¹⁶⁵ R. C. Moore, M. K. Elias, and N. D. Newell, *Pennsylvanian and Permian rocks of Kansas*, State Geol. Surv. of Kansas, stratigraphic section printed 1935.

¹⁶⁶ Harold R. Wanless and J. Marvin Weller, *Correlation and extent of Pennsylvanian cyclothem*, Bull. Geol. Soc. Amer., vol. 43, p. 1003, 1932.

tongues extending from the west. These may be partially developed cyclothems that failed to go beyond the chemically precipitated limestone stage except in one instance where a pelecypod-bearing limestone extends eastward for 100 miles or more. Comparable limestone units also are found in the red beds at the top of the Kaibab formation to the west, but these have not been studied in detail.

The origin and significance of cycles in the Pennsylvanian sediments of Illinois have been discussed by Weller and Wanless. At first they thought that the unconformities were due to periods of diastrophism.¹⁶⁷ Later, Wanless states that he considers the "phenomenon of cyclic sedimentation [too] widespread in the late Paleozoic rocks of the northern hemisphere, [and] the individual strata involved in the cycles extend too far to be the results of local diastrophism, but that the phenomenon could be more readily explained by world-wide eustatic changes in sea level. . . . these changes might be the result of the alternate growth and wasting of ice sheets, principally in the southern hemisphere."¹⁶⁸

The character of the sequence and also the relation of stages in sedimentation to periods of change in base level in the Permian are decidedly different from those in the Pennsylvanian. In addition to these differences, the great thickness of beds in most of the units of the Toroweap and Kaibab cyclothems argues strongly against glaciation as a cause.

Cycles in deposition which are probably comparable with those of the Toroweap and Kaibab formations are found in the "intertongued" portions of the Permian of southeastern Wyoming. In sections of these deposits, red sediments alternate with typical *Phosphoria* limestones and sandstones and, according to Thomas, the latter types indicate transgressions of the sea which "were rapid and probably of short duration, for some of the limestone tongues, although thin, cover hundreds of square miles."¹⁶⁹ The cause of this cyclic development, he states, is probably to be found either in oscillatory movements of the sea or in periodic uplift of land masses which supplied red elastic material. Either might cause the clear-water zone favorable to limestone deposition to retreat.

In the case of the Toroweap and Kaibab formations the explanations offered by Thomas for the Wyoming Permian may also apply. Because the red sediments in the Arizona formations, if derived from a mountainous area, had to be transported a great distance across flat plains, however, it seems improbable that uplift or cessation of uplift at the source would have greatly affected the area of deposition. Furthermore, marine sediments above playa deposits indicate that the sea level must have been raised or the land lowered at this point. In brief, the writer believes that the most logical explanation for these cycles is to be found in earth movements in the region of deposition.

¹⁶⁷ *Ibid.*, p. 1016.

¹⁶⁸ Harold R. Wanless, personal communication, January 8, 1936.

¹⁶⁹ Horace D. Thomas, *Phosphoria and Dinwoody tongues in lower Chugwater of central and southeastern Wyoming*, Bull. Amer. Assoc. Petrol. Geol., vol. 18, no. 12, p. 1693, 1934.

Minor Cycles

Cycles in sedimentation occur in certain of the near-shore facies of the β member of the Kaibab formation. These include the "limestone-bedded chert" sequence in facies 2 and the "limestone-sandstone" sequence in parts of facies 4. These are referred to as minor cycles, as they occur locally within a division of a major cycle. They are discussed separately, furthermore, because they appear to have a different origin.

The "limestone-bedded chert" cycles of facies 2 have been discussed in detail in the section of this chapter on cherts. They consist of the following types of deposits, which are repeated many times in a vertical section:

3. Fossiliferous sandy limestone
2. Barren sandy limestone
1. Bedded chert

Considerable evidence indicates that this type of cycle, occurring in beds between the marine limestone and the near-shore sandstones, is the result of periodic supersaturation of sea water with silica, which causes silica deposition and at regular intervals creates conditions unfavorable to life.

A cycle consisting of limestone and sandstone (plate 3*b*) is repeated numerous times in the β member of the Kaibab formation in the vicinity of Chevelon Canyon, south of Winslow, Arizona, and farther east. The beds of this member, which form the sheer walls of various small canyons in the neighborhood, are massive and thick and a complete cycle is represented by each bed. The change from impure dolomitic limestone, containing a moluscan fauna, to fine-grained calcareous sandstone without fossils is one of transition. This gradation in each bed from one type of sediment to another is probably to be explained by changes of power in the transporting agent that introduced the clastic sand grains. These changes might be due to climatic pulsations or to tectonic influences.

IV. ECOLOGY, PHYSICAL GEOGRAPHY, AND CLIMATOLOGY

In preparing this chapter the writer is well aware of the fact that he is dealing with subjects for which in many cases there is only meager evidence upon which to base discussion; that therefore some of his conclusions must be regarded as highly tentative. He realizes also that this general field has seldom been treated in detail in geological papers; that is, its principles have not often been applied to particular formations or faunas. Nevertheless, with the amount of detailed data now available on the stratigraphy, the sedimentation, and the palæontology of the formations under consideration, and with the almost unique opportunities for seeing relationships between units in the field, it seems desirable to attempt a discussion of the ecological aspects as well as the climatic and geographic phases of the problem. In one sense these constitute the most important results of this environmental study.

Marked variations both in type of sediment and in fauna along different portions of any modern shore line are features that are commonly observed and are usually taken for granted, yet similar changes in the rock record of the past are often overlooked or misinterpreted. Kindle called attention of palæontologists to the importance of such changes when he stated that "the lithologic facies is subject to abrupt changes in waters of the same depth, which are responsible for sharply contrasting faunal facies along different parts of the same coast line."¹ An excellent demonstration of how dissimilar groups of animals may be contemporaneous and live in fairly close proximity has been found in the detailed studies of foraminifera off southern California by Natland.² He shows conclusively that "the resemblance of two assemblages indicates similar environments but not necessarily contemporaneity."

In the extensive literature on the Permian rocks of northern Arizona and southern Utah the only reference known to the writer to the possible part played by environment in controlling the aspects of faunas is found in a comparison by Girty of the Hermosa and Rico fossils. He states that although the faunal contrast is great (one a brachiopod assemblage, the other a molluscan), "the character of this change is such as might readily be a response to a change in local conditions of environment as well as something more widespread and fundamental."³

In both the Toroweap and Kaibab formations several contrasted faunal assemblages are found, each a reflection of environmental influences, yet

¹ E. M. Kindle, *Rôle of facies in stratigraphic paleontology*, Proc. Geol. Soc. Amer., p. 423, 1933.

² Manley L. Natland, *The temperature- and depth-distribution of some recent and fossil foraminifera in the southern California region*, Bull. Scripps Inst. Oceanography, Tech. Ser., vol. 3, no. 10, pp. 225-230, 1933.

³ G. H. Girty, in Baker and others, *Notes on the stratigraphy of the Moab region, Utah*, Bull. Amer. Assoc. Petrol. Geol., vol. 11, no. 8, p. 793, 1927.

nearly or exactly contemporaneous with the others, not the result of widespread evolutionary changes. Recognizing this important point, it is now proposed to analyze, as far as possible, each environment represented, and to deduce something of the controlling factors.

FACTORS CONTROLLING FAUNAL ASSEMBLAGES

Organisms of the sea are classed under three distinct types: the plankton, the nekton, and the benthos. As only the last mentioned is narrowly limited in distribution by the nature of the bottom, it alone fully reflects the environment in which it is found. Representatives of the floating or swimming types, although commonly influenced by temperature, currents, chemical and physical character of the water, and food supply, usually have little relation to the environment of the sediments in which their skeletons may be preserved. Thus, a tooth of the shark *Deltodus mercurii*, found in the sandstone of facies 3 of the Kaibab formation (β member) along with numerous mollusks, might have been buried in any other facies of the formation and with a totally different association of fossils.

The matter of entombment of animals should always be considered with care in order to avoid incorrect inferences regarding the original environment of the assemblage. Not only are the plankton and nekton usually buried in an environment foreign to that in which they lived, but even the benthos is sometimes preserved in totally new surroundings. As an example, coastal sand dunes of Hawaii were found by Hinds⁴ to contain many marine invertebrates and a few land snails. Another example is found in the Caspian Sea, where enormous quantities of organisms, according to Twenhofel,⁵ are carried by strong currents into the very salty and entirely foreign environment of the Kara Bughoz, where scant life exists. Therefore, whenever fossils are found in sediments of types with which such fossils are not normally associated, they should be used with care in the interpretation of the geologic record.

The significance of lack of fossils in sediments is sometimes difficult to determine. Their absence does not necessarily imply a scarcity of life on the sea bottom, but may result from destruction of organic matter by scavengers. Thus, fucoid-covered surfaces in the Kaibab formation, β member, facies 2 and 3, which apparently were developed through the activities of boring worms (see plate 39), may well explain why no other invertebrate fossils occur in those beds, although they are present in similar adjacent ones.

Absence of fossils may be due to still other causes. Even though rapid burial virtually insures their preservation,⁶ forces operating subsequently may destroy them. Recrystallization and other secondary processes may remove all traces of them. An example of beds from which fossil animal

⁴ N. E. A. Hinds, Bull. Bishop Mus., no. 71, p. 72, 1930.

⁵ W. H. Twenhofel, *Environment in sedimentation and stratigraphy*, Bull. Geol. Soc. Amer., vol. 42, p. 418, 1931.

⁶ *Ibid.*, p. 422.

remains have been eradicated is probably to be found in the dolomitic limestone facies of the Kaibab formation (β member, facies 4), for it seems likely that a prolific molluscan fauna was once present in it. Certain beds are literally speckled with small geodes which apparently were once fossils, as shown by some examples in which the original outlines are still well defined.

When it has been determined that certain fossil assemblages in a formation are representative of the environment indicated by a particular group of sediments, it is then important from the standpoint of palæogeography to determine the nature of this environment. The following physical factors are listed by Kindle⁷ as those most likely to control the character of a faunal facies: (1) bottom character, (2) temperature, (3) depth, (4) marine currents, (5) salinity, (6) amount of light. To these might also be added a seventh important factor, turbidity.

Some physical factors that may affect the environment of any particular facies⁸ have their character recorded in the lithology. Examples are the type of bottom and the salinity. The importance of certain other factors such as water agitation, currents, and turbidity that must also have affected the animals of each facies may be inferred from various forms of indirect evidence. For still other factors, however, it is difficult to ascertain anything of their character and influence during sedimentation. Fortunately for this study, those forces most critical in their effect on environment are also those for which most data are now available.

In this discussion each of the physical factors enumerated above is considered in turn and, wherever available, evidence of its effect on sediments and life of the Toroweap and Kaibab formations is given. In addition, the environmental factors influencing each facies in these formations are summarized in tabular analysis.

Bottom Character

The importance of bottom character as an environmental factor is well recognized. It should be remembered, however, that the physical character of the bottom is in part due to and therefore interrelated with other factors such as depth, water agitation, and temperature. Sumner, from his intensive studies on the New England coast, states that it is "foremost among the conditions determining the distribution of the bottom-dwelling organisms."⁹ Herdman¹⁰ reached the same conclusion during studies of faunas and sediments in the Irish Sea, and Twenhofel speaks of it as "the most important and profound factor of the environment determining the

⁷ E. M. Kindle, *Rôle of facies in stratigraphic paleontology*, Proc. Geol. Soc. Amer., p. 422, 1933.

⁸ "Facies" as used in this paper refers to a lateral subdivision of a member having a distinctive lithology, fauna, or both.

⁹ F. B. Sumner, *An intensive study of the flora and fauna of a restricted area of sea bottom*, Bull. U. S. Bur. Fisheries, vol. 28, pt. 2, pp. 1225-1264, 1928.

¹⁰ W. A. Herdman, *The marine zoology of the Irish Sea*, Rept. Brit. Assoc. Adv. Sci., pp. 318-334, 1894.

character of the benthos.”¹¹ Further testimony on this point is found in Agassiz’s statement that “the nature of the bottom, far more than the depth is the cause of the abrupt changes of fauna which are observed when we pass from one kind of bottom to another.”¹²

Specific examples of the effect on and control of modern bottom-living organisms by the character of the sea floor are numerous and striking. In San Francisco Bay, Packard¹³ found the average number of living mollusks per station on the muddy bottom to be 38.4, as contrasted with only 5.2 on the sandy bottom. In the Bay of Naples, comparing the faunas on a mud floor and a calcareous sand floor in close proximity, Walther¹⁴ in 1885 found 45 hard-shelled species on the former and 310 on the latter, with only 14 common species. Twenty-five years later he found a complete faunal change which had accompanied a change in bottom character. Still another excellent example of bottom control of fauna was found by Kindle¹⁵ from dredging in the Bay of Fundy. An analysis of specimens from stations in the black mud, intertidal zone, rock and sandy bottoms, and sandy mud showed that of a total of 51 species of pelecypods and gastropods, only 3 were common to all environments.

Illustrations of the effect of sea bottom on faunas are not difficult to find in the Toroweap and Kaibab formations; however, in some places marked changes in fauna occurred without relation to bottom character. For example, in the limestone member (β) of the Toroweap, the complete faunal change from west to east can scarcely be due in any large degree to different types of bottom. Although the brachiopods, bryozoeae, and crinoids of facies 1 are replaced entirely by an assemblage of pelecypods and gastropods in facies 2, the sea bottom of both facies was largely a calcareous ooze, and differed only in the presence of a small amount of elastic sand in the eastern area. Likewise in the Kaibab formation, the small amount of detrital matter in many parts of the limestone of facies 4 suggests that there also, changes in sea-floor character were not commensurate with the contrasts observed between faunas of adjoining facies.

Evidence that the character of the sea bottom was very significant in accounting for faunal differences in facies 1, facies 2, and facies 3 of the Kaibab formation (β member) is strong. From a sea floor composed entirely of calcareous ooze in facies 1, the introduction of and decided increase in siliceous sand grains eastward through facies 2 was certainly an important factor in causing the coral and brachiopod fauna to disappear.

¹¹ W. H. Twenhofel, *Environment in sedimentation and stratigraphy*, Bull. Geol. Soc. Amer., vol. 42, p. 411, 1931.

¹² A. Agassiz, quoted by L. F. Pourtales in *Three cruises of the "Blake,"* vol. 1, Bull. Mus. Comp. Zool., vol. 14, p. 285, 1888.

¹³ E. L. Packard, *Molluscan fauna from San Francisco Bay*, Univ. Calif. Pub. Zool., vol. 14, p. 245, 1918.

¹⁴ Walther, quoted in W. H. Twenhofel, *Environment in sedimentation and stratigraphy*, Bull. Geol. Soc. Amer., vol. 42, p. 412, 1931.

¹⁵ E. M. Kindle, *Bottom control of marine faunas as illustrated by dredging in the Bay of Fundy*, Amer. Jour. Sci., 4th ser., vol. 41, pp. 449–461, 1916.

In facies 3, still farther east, the bottom was entirely covered with uniform, fine-grained sand, which amply explains why the assemblage of mollusks found there is unique.

From his researches in San Francisco Bay, Packard ¹⁶ found a bottom of pure sand to be unfavorable to a varied molluscan life. Verrill ¹⁷ likewise refers to true sandy bottoms as unfavorable to many kinds of animals. These cases obviously represent sand-bottom environments different from that represented by facies 3 of the Kaibab formation, where an abundant but unique fauna occurs. Modern sand environments, likewise favorable to life, are referred to in Twenhofel's paper on "The ecology of sand areas," ¹⁸ where he notes that, on some sand bottoms, the population may be as abundant as on bottoms composed of other materials, but the kinds of individuals are very likely to be different. He cites as examples findings of Sumner ¹⁹ on the sand bottom of Vineyard Sound and of Allen ²⁰ along the coast near Plymouth, England.

A cause of some pure sand areas being favorable to life and others highly unfavorable is presumably to be found in the stability of the deposits in some cases and their shifting character in others. Thus, in the sand facies of the Kaibab formation, steady, constant sedimentation, indicated by uniform texture and massiveness of beds, is probably a factor which made the environment favorable to a large fauna and to its entombment.

Salinity or Brackish Nature of Water

There is no doubt that either increased salinity or brackish character greatly affects the inhabitants of a sea. These factors may even form an efficient barrier to life, as in the case of the exceptionally saline waters, due to excessive evaporation, off the west coast of northern Africa.²¹ In essentially every instance they constitute a specialized environment and usually suggest local, isolated areas such as gulfs or bays, lagoons or small inland seas. Faunas, where present under conditions such as these, may be expected to have minor unique variations or strongly accentuated peculiarities of structure, so are "provincial" or "local," in contrast with those developed in wide areas of similar conditions where commingling of forms tends to maintain the mean of life. Thinness or thickness of shell and pauperization are characteristics of provincial faunas.

¹⁶ E. L. Packard, *Molluscan fauna from San Francisco Bay*, Univ. Calif. Pub. Zool., vol. 14, p. 245, 1918.

¹⁷ A. E. Verrill, *Report on the invertebrate animals of Vineyard Sound and the adjacent waters*, Rept. U. S. Comm. Fish and Fisheries, p. 425, 1871-1872.

¹⁸ W. H. Twenhofel, *The ecology of sand areas*, Jour. Paleontol., vol. 9, no. 1, p. 280, 1935.

¹⁹ F. B. Sumner, *An intensive study of the flora and fauna of a restricted area of sea bottom*, Bull. U. S. Bur. Fisheries, vol. 28, pt. 2, pp. 1225-1264, 1928.

²⁰ E. J. Allen, *On the fauna on bottom-deposits near the thirty-fathom line from the Eddystone Grounds to Start Point*, Jour. Marine Biol. Assoc., vol. 5, pp. 365-542, 1897-1899.

²¹ E. C. Case, *The environment of vertebrate life in the late Paleozoic in North America: a paleogeographic study*, Carnegie Inst. Wash. Pub. No. 283, p. 39, 1919.

The effects of saline or brackish-water conditions in various near-shore facies of the Toroweap and Kaibab formations are suggested by the numerous provincial faunas that have been recognized in the sediments. The highly magnesian character of most of the limestones and the association in some instances with gypsum deposits, chemical limestones, and red beds indicate various degrees of salinity in certain of the waters under which the beds were laid down. Other beds no doubt were formed in basins that were brackish in character owing to streams pouring in fresh waters.

Facies 2 in the β member of the Toroweap formation and facies 4 of the Kaibab β member are good examples of deposits that appear to have been laid down beneath near-shore, highly saline or brackish waters. There is no evidence whatsoever in either case that these waters were isolated from those of the open seas to the west; nor does field evidence indicate that their contrasted faunas were separated by sedimentary barriers. Taking into consideration the steadily increasing magnesium content from west to east in these formations, together with the lack of evidence from the sediments that bottom character, depth, turbidity, and other factors varied greatly in the corresponding open-sea and near-shore facies under consideration, it seems probable that degree of salinity was the major cause in the replacement of the brachiopod-bryozoan-horn coral faunas by the molluscan faunas to the east.

In the fossiliferous, thin-bedded limestones of the Kaibab α member, which are comparatively local in character and in many places interbedded with red beds, chemical limestones, or even gypsum deposits, the provincial character of the faunas is to be expected. These deposits were unquestionably formed in residual basins or lagoons, probably partly cut off from the sea as it retreated westward and southward from the area. Such an explanation accounts for the fine-grained character of the limestone and its very high magnesium content, as well as the entire replacement of open-sea faunas by one of mollusks.

The pure sand facies (no. 3, β member) of the Kaibab formation probably represents an area of brackish waters, for the elastic grains suggest the proximity of a large stream. The specialized character of the fossils is in accord with this assumption but does not prove its validity, since bottom character alone is sufficient to account for the unique fauna.

A probable effect on life under either highly saline or brackish conditions in the Toroweap and Kaibab formations appears to be a dwarfing of certain species. That such dwarfing was due to salinity or brackishness of the water alone cannot be assumed, for turbidity and temperature changes are other possible causes. Nevertheless, because there is little evidence in the sediments that the waters were excessively turbid and no reason to believe that temperature changes were especially different in the open-sea and near-shore facies, salinity remains as the most probable factor. The dwarfing is best illustrated in the brachiopods—those few hardy species which apparently were able to exist in an environment that barred the entrance to

their relatives of the open seas. Mollusks probably also were dwarfed, but examples are less numerous.

Evidence of dwarfing of faunas is found in modern waters. Perhaps the most striking example known to the writer is that of Pechili Bay in China, described by Grabau.²² In this case a nearly enclosed body of water bordering the Yellow Sea, receiving great quantities of fresh water from the Yellow River, has caused animal life to be much modified, the types of change being similar to those noted in the near-shore facies of Toroweap and Kaibab formations. Brachiopods, corals, and echinoids, reported as fairly common in the Yellow Sea, are rare and commonly dwarfed in the bay. The pelecypods and gastropods of the open sea are said to be abundant in the brackish waters but in many examples are not more than half normal size.

TABLE 13. ANALYSES OF WATER FROM GULF OF PECHILI AND YELLOW SEA

	Gulf	Yellow Sea
Salinity.....	25.54 per mille	35.00 per mille
NaCl.....	52.16 per cent	77.76 per cent
MgCl ₂	32.16 per cent	10.88 per cent
MgSO ₄	9.46 per cent	4.74 per cent

Water analyses of these two areas are given in table 13. While this makes a pertinent comparison, it should be kept in mind that, in the modern case, certain other factors such as turbidity and bottom character doubtless also exert an important influence on the life.

One other ecological aspect possibly related to the question of salinity of the water deserves mention. The general lack of reef corals in deposits of these Permian seas, which, away from their borders, apparently were clear, is a feature not easy to explain. Following the Carboniferous, when such organisms were extremely abundant in many places, their absence is especially noticeable. It might possibly be ascribed to temperature changes, accompanying glaciation in the southern hemisphere, but other types of life give no indication of this. Increased salinity, even in the open seas, resulting from the generally arid, desert-like conditions of the time seems to the writer to be a possible factor.

Agitation and Currents

Wave action as an influence on molluscan faunas has been pointed out by Kindle,²³ and an excellent illustration of its direct result on faunas has been described by Vaughan.²⁴ On the Cocos Keeling Islands of the West Indies, Vaughan found 23 species living in the lagoon back of the reefs, 20

²² A. W. Grabau, *The Permian of Mongolia*, vol. 4 of *Natural history of central Asia* (New York: American Museum of Natural History), 1931.

²³ E. M. Kindle, *Bottom control of marine faunas as illustrated by dredging in the Bay of Fundy*, Amer. Jour. Sci., 4th ser., vol. 41, p. 421, 1916.

²⁴ T. W. Vaughan, Smithsonian Rept. for 1917, pp. 195-196, 1919.

species in the barrier pools and on the barrier flat, and 16 species on the exposed barrier. Of the 23 species of the lagoon, only 3 were found on the exposed barrier.

Although wave action and other types of water agitation must be recognized as important influences in any environment, there is little in the sedimentary record of the Toroweap and Kaibab formations to indicate their effects. Obviously the coarsely crystalline limestones with their clear-water faunas represent environments where current or wave disturbances were at the minimum, but even in near-shore facies with elastic sands indicating water movement, there is no evidence of violent surf or local currents.

Major ocean currents, likewise, should be recognized as important in maintaining or altering marine facies. It was noted by Agassiz,²⁵ for example, how closely the limits of the siliceous sand bottom in the Atlantic coincided with the boundaries of the cold current from the north, while the calcareous deposits corresponded to the course of the warm Gulf Stream. Only to the extent that they are reflected in the bottom sediments, however, can the existence of such currents be detected in the rock record, hence the part played by them in the history of the Toroweap and Kaibab formations remains unrecognized.

Turbidity

The effects of suspended sediments on aquatic life may be very great. This point has been well illustrated by Bartsch,²⁶ who shows that mud and silt carried by the Missouri River into the Mississippi form a complete barrier to *Unios* from the junction of the streams down. Natland,²⁷ from his studies of foraminifera off the coast of southern California, found that the rate of sedimentation largely controls the abundance of these animals. Furthermore, it is well known that certain types such as corals and some bryozoa, living in fixed positions with mouths and tentacles directed upward, will speedily become extinct in an area invaded by falling sediment. Thus it is seen that the susceptibility of marine animals to ill effects from turbidity varies greatly and must be evaluated separately for each animal group.

Applying generalizations regarding the effect of turbid waters on life to the Toroweap and Kaibab formations, it becomes readily apparent that the open-sea limestones of these formations, with their many corals, crinoids, and bryozoa, must have been deposited in clear waters; but the other limestone facies offer no evidence in their faunas regarding this point. Examination of the sediments in these other facies, however, gives little reason

²⁵ A. Agassiz, quoted by L. F. Pourtales in *Three cruises of the "Blake,"* vol. 1, Bull. Mus. Comp. Zool., vol. 14, p. 279, 1888.

²⁶ Paul Bartsch, *The Missouri River as a faunal barrier*, Nautilus, vol. 30, no. 8, p. 92, 1916-1917.

²⁷ Manley L. Natland, *The temperature- and depth-distribution of some recent and fossil foraminifera in the southern California region*, Bull. Scripps Inst. Oceanography, Tech. Ser., vol. 3, no. 10, p. 229, 1933.

to think that there was much mud or even, in most cases, an amount of fine sand unfavorable to the growth of marine life other than the sessile forms. On the other hand, if the red-bed facies of the Toroweap and Kaibab actually represent facies associated with marine deposition, they show environments in which turbidity must have been far too high for development of molluscan life.

Temperature

An evaluation of the importance of temperature effects on invertebrate fossils is difficult to make largely because evidence must necessarily be indirect and also because it is closely interrelated with other controlling forces. Its probable importance, nevertheless, is brought out by a study of life zones among modern foraminifera, made by Natland,²⁸ off the coast of southern California. He discovered that in the shallower depths where temperatures varied in short distances, there was a correspondingly great variation in fauna, while in the deeper part of the channel where temperature changes are slight, even with an increase in depth of several thousand feet, the changes in the foraminiferal fauna are much less. From this he concluded "that temperature had a far greater influence than depth on some foraminifera."

Little can be said with any degree of certainty regarding temperatures in the Toroweap-Kaibab seas. Evidence is abundant indicating that in the areas studied, the seas at no place and at no time were very deep and conditions must have been remarkably uniform in most of the open-sea portions. Nearer shore and in the relict basins left as the seas retreated, the very shallowness of the waters and, in some places, the landlocked conditions cutting off circulation no doubt made temperatures quite distinctive in each facies.

Depth

The depth at which animals live also controls the amount of available light, pressure, temperature, and certain other factors such as degree of water disturbance, thus depth is an important factor in the control of bottom life. Examples of the effect of this influence are numerous. In speaking of lacustrine deposits, Kindle notes that "the great bulk of the plant life and the molluscan fauna is found inside the fifty foot contour and few kinds of mollusks live in depths below thirty feet."²⁹ In marine waters the vertical range of such invertebrates is usually considerably greater but life is just as definitely controlled in its distribution. Forbes³⁰ states that marine bivalves are able to occupy a greater bathymetric range than univalves, thus explaining why fossils of one class of mollusca may indicate correlative formations, while those of another do not.

In the geologic record, facies changes have often been explained as due

²⁸ *Ibid.*, p. 227.

²⁹ E. M. Kindle, *Bottom control of marine faunas as illustrated by dredging in the Bay of Fundy*, Amer. Jour. Sci., 4th ser., vol. 41, p. 419, 1916.

³⁰ Edward Forbes, New Philos. Jour. Edinburgh, vol. 51, p. 389, 1851.

to depth control of organisms. Twenhofel³¹ cites references by Bittner to faunal variations in the Bohemian Massiv, by Kiar to the Norwegian Silurian, and by McLearn to the Arisaig Silurian of Canada, all attributed to bathymetric influences. As stated by him, these changes are accompanied in some cases at least by lithologic changes, therefore it is not at all certain that depth was a factor or at least the sole factor in causing the different facies. In brief, the interrelationship between many of the factors controlling a faunal facies is often such as to make recognition of one critical factor difficult or impossible.

Some evidence has been presented, indicating that depth is probably not as important in influencing marine life as are several of the other factors discussed. Agassiz³² states of the Atlantic coast that the nature of the bottom far more than the depth is the cause of the abrupt changes of fauna which are observed in passing from one kind of bottom to another. A second case is that of Natland,³³ who found from his studies of foraminifera in connection with faunal—or life—zones off the California coast that apparently “temperature has a far greater influence than depth on some foraminifera.”

It is readily apparent from the preceding discussion that determination of the amount of influence which depth has had in creating distinct facies of a formation is extremely difficult. In the cases of the Toroweap and Kaibab it seems definitely established that none of the deposits was laid down beneath waters of great depth, even when they were obviously far from shore. The abundance and character of life represented in nearly all the limestones as well as various features of sedimentation indicate this. Even the barren or nearly barren limestones are readily explained as shallow-water types in which paucity of organisms was due to high concentration of salts rather than to depth. Aside from this generalization, little information can be given regarding bathymetric influences on the recognized facies of the formations, and it can be assumed only that such influences had some importance.

DISTRIBUTION AND DISPERSION OF INVERTEBRATE LIFE

The general distribution of the faunal and lithologic facies of the Toroweap and Kaibab formations has already been discussed. The association of brachiopods, corals, bryozoa, crinoids, and pecten-like pelecypods in the areas of open sea and the confinement of most mollusks, scaphopods, trilobites, and cephalopods to deposits of the restricted water bodies of more saline or more brackish character are clearly demonstrated. These repre-

³¹ W. H. Twenhofel, *Environment in sedimentation and stratigraphy*, Bull. Geol. Soc. Amer., vol. 42, p. 414, 1931.

³² A. Agassiz, quoted by L. F. Pourtales in *Three cruises of the “Blake,”* vol. 1, Bull. Mus. Comp. Zool., vol. 14, p. 285, 1888.

³³ M. L. Natland, *The temperature- and depth-distribution of some recent and fossil foraminifera in the southern California region*, Bull. Scripps Inst. Oceanography, Tech. Ser., vol. 3, no. 10, p. 227, 1933.

sent normal conditions of the Permian period and should need no further explanation. It is proposed now to discuss some of the abnormal features of ecology.

Unusual Accumulation

One of the amazing features of faunal distribution in the Toroweap formation is represented by the pelecypod zone near the top of the α member. At this horizon, many millions of shells of the genus *Schizodus* (?) have been accumulated. They are closely spaced throughout a limestone bed that, over a vast area, is everywhere about 3 feet thick (plate 6b). This limestone, located between silt beds, has been observed near the Kaibab Trail to the east and as far west as the Aubrey Cliffs and the Shivwits Plateau (Parashant Canyon), air-line distances of 67 and 72 miles. It is a dependable marker bed, having been found in all intermediate sections examined, everywhere with about the same thickness and with the same abundance of one species of mollusk throughout.

Parallels to the case of the pelecypod zone just cited are probably to be found in certain oyster deposits of today. Nearly a thousand square miles between Charlestown and Biscayne Bay, formerly water of moderate depths, are said by Shaler³⁴ to be filled now to high-tide level by sediments largely composed of oyster shells. Kindle has described how "the common oyster, in southern waters where the destructive starfish is absent, rapidly destroys its habitat in shallow sounds and bays with its accumulated shells," also how succession "frequently results from rapid deposition of mud and consequent smothering of the oyster bed."³⁵

In the case of the Permian deposits, the presence of only one species throughout the bed suggests that this was a prolific form, in a favorable environment and with no enemies present. Ulrich³⁶ has discussed how relatively rapidly even mollusks may be dispersed, and here, certainly, is confirmation of his view. Following this development, destruction doubtless resulted, as in the case of the modern oysters, either from the spoiling of the habitat by the animals themselves or from their smothering by the influx of overlying silts.

Spotty Distribution

What might be termed the "spotty distribution" of many species of mollusks and molluscoids throughout various beds in the Toroweap and Kaibab formations is noticeable to one who has examined the details of these strata. Local accumulations or the absence of species in various parts of beds that are essentially uniform throughout may be explained in numerous ways. Destruction by scavengers, concentration by currents, and even a later removal of fossil remains after or during the rock-forming

³⁴ N. S. Shaler, *Sea and land* (New York: Charles Scribner's Sons), p. 245, 1894.

³⁵ E. M. Kindle, *Bottom control of marine faunas as illustrated by dredging in the Bay of Fundy*, Amer. Jour. Sci., 4th ser., vol. 41, p. 413, 1916.

³⁶ E. O. Ulrich, *Revision of the Paleozoic systems*, Bull. Geol. Soc. Amer., vol. 22, pp. 295, 575, 1911.

processes are obvious possibilities. In general, however, and especially in local areas where great accumulations of one species occur, the writer believes the cause is to be found in the natural habits of such animals. That this is the case on sea coasts of today is pointed out by MacGinitie, who observed of the life forms in a California marine estuary, "They all seem to have either a preference for a certain locality or a gregarious instinct which causes them to occur in colonies."³⁷

Accidental Introduction

As defined by Case, accidental introduction is "the sporadic dispersal of individuals as opposed to the migration of an entire or a large portion of a fauna or flora"³⁸ and may be the result either of the movements of living individuals or of the transportation of their bodies after death. Many examples of accidental introduction of brachiopods, especially productids, into environments that obviously were not normal to them have been noted in the rock records of the Kaibab and Toroweap formations.

Productus ivesi, the commonest brachiopod in the Toroweap formation, had its normal habitat in the marine waters beneath which the facies 1 limestones were deposited. This species, however, has also been found far to the east associated with the mollusks of facies 2. Similarly in the Kaibab formation, *Productus bassi* has been recorded from deposits very different from and distant from those of the open sea in which its adaptability and prolific nature allowed it to become so abundant. Isolated specimens have been observed in the β member as far east as Grand Falls on the Little Colorado and from the "lagoonal" limestones of the α member, in both cases associated with mollusks.

In the examples of "accidental" introduction just cited, the productids probably entered the abnormal environments during life, not afterward. This is suggested by the fact that in each instance the shells were below average size for the species, as if dwarfed by development under adverse conditions. Furthermore, as these undoubtedly were the most hardy and best-adapted brachiopod types of their times, they were able to extend their ranges farther and to exist under more adverse conditions than their associates, as shown by their continued abundance in shoreward deposits, beyond the limits of areas containing other brachiopods.

Second only to the large productids in their hardiness and ability to live under contrasting environmental conditions were the *Chonetes kaibabensis*, found also occasionally in the α member and the near-shore facies of the β member in the Kaibab formation. All other brachiopod species apparently were rigidly controlled in distribution by the environmental factors of facies 1.

³⁷ G. E. MacGinitie, *Ecological aspects of a California marine estuary*, Amer. Mid. Naturalist, vol. 16, no. 5, p. 668, 1935.

³⁸ E. C. Case, *The environment of vertebrate life in the late Paleozoic in North America: a paleogeographic study*, Carnegie Inst. Wash. Pub. No. 283, p. 37, 1919.

Adaptive Radiation

It has been stated by Case that radiations represented by fossils "may well be the key to the geographic conditions of the time."³⁹ If this be true, the marine faunas of the Kaibab and Toroweap formations constitute confirmation of the chronological sequence of events of this period as suggested by the lithologic record.

Considering "adaptive radiation" to mean the increase both in number of individuals and in varieties, species, and genera, reaching out in all directions to find unoccupied niches in the scheme of things,⁴⁰ the evidence of its effects during the time that the Toroweap and Kaibab sediments were accumulating will be examined.

First, the marine invasion represented by the limestones of the Toroweap formation was the earliest in northern Arizona and southern Utah during Middle Permian time and followed a long period of continental deposition. As might be expected, the fauna in it was quite limited in both number and variety of genera and species, and the ones included were only those forms known to be especially prolific and adaptable throughout the Permian.

The withdrawal of the sea after the first Middle Permian invasion in Arizona and southern Utah was not for long, geologically speaking, and the environment apparently was much the same when the second Middle Permian Sea (represented by the Kaibab formation) advanced. With it returned most if not all of the invertebrates of the earlier sea, either the same or only subspecifically different. This time, however, many additional forms also made their appearance, no doubt the result of adaptive radiation. Among these were some of the more highly specialized Permian species that were apparently delicately adjusted to a definite environment.

The retreat of the second Middle Permian sea from this region marked the end of marine conditions until the Triassic. Even from a geological standpoint the time must have been long, for during this interval invertebrate faunas of changed character were developed, as seen in the Triassic Moenkopi formation. In the limestones of this formation nearly all the brachiopod types characteristic of the Permian are missing. This then is an example of what Kindle must have had in mind when he said, "Changes . . . involving complete or universal extinction of many species of wide distribution, such as may result from the development of a continental ice cap or the extensive transgression of seas, produce faunal changes of the order on which geological systems should be based."⁴¹ Furthermore it illustrates Ulrich's⁴² belief that little evolution has taken place within the

³⁹ *Ibid.*, p. 26.

⁴⁰ H. F. Osborn, *The law of adaptive radiation*, Amer. Naturalist, vol. 36, p. 353, 1902.

⁴¹ E. M. Kindle, *Bottom control of marine faunas as illustrated by dredging in the Bay of Fundy*, Amer. Jour. Sci., 4th ser., vol. 41, p. 411, 1916.

⁴² E. O. Ulrich, *Revision of the Paleozoic systems*, Bull. Geol. Soc. Amer., vol. 22, p. 498, 1911.

TABLE 14. ATTEMPTED EVALUATION OF ENVIRONMENTS IN TOROWEAP AND KAIBAB FACIES

	Bottom character	Salinity	Agitation	Turbid-ity	Temperature	Depth	Light
Toroweap β :							
Facies 1.....	Calcareous; no sand or mud	Normal	None	None	Warm and even	Mod- erate	Much
Facies 2.....	Fine sand and calcareous ooze	Probably more brackish	Slight	Slight	Same	Shallow	Same
Kaibab γ :							
Facies 1.....	Calcareous	Probably more concentrated	No evidence	?	Same	Shallow	Same
Kaibab β :							
Facies 1.....	Calcareous; no sand or mud	Normal	None	None	Same	Mod- erate	Same
Facies 2.....	Fine sand; siliceous and calcareous ooze	Probably more brackish	Slight	Slight	Same	Shallow	Same
Facies 3.....	Very sandy bottom	Probably more brackish	Considerable	Much	Same	Shallow	Same
Facies 4.....	Locally sandy; mostly calcareous	Probably more concentrated	Local, if any	?	Same	Shallow	Same
Kaibab α :							
Facies 1.....	Locally sandy; mostly calcareous	Probably more concentrated	Local, if any	?	Same	Very shallow	Same
Facies 2 and 3.....	Locally sandy; mostly calcareous	Probably more concentrated	Local, if any	?	Same	Very shallow	Same

epicontinental seas, but that most of it was in the ocean basins when the seas withdrew.

. PHYSICAL GEOGRAPHY

General Features

Despite the diversity of character and the many variations in sedimentation found in vertical sections of the Toroweap and Kaibab formations, certain generalizations regarding the geographical conditions amid which they were deposited are at once apparent. The region in all probability was low and level over great areas; the lands bordering the seas were featureless and the seas shallow and flat-bottomed. Extreme fineness of the clastic sediments everywhere testifies to the character of the surrounding terrain, while the remarkable uniformity of the thick limestone members over thousands of square miles gives evidence of sea bottoms covered with calcareous ooze.

Cycles of deposition in various parts of each formation, thin-bedded limestones, and intraformational conglomerates all suggest stages in sedimentation when frequent interruptions and rapid changes took place. Large sluggish streams apparently introduced much fine clastic material from the adjoining areas. Furthermore, submergences and emergences of the region allowed the seas to advance and retreat over this terrain, shifting with them for great distances the mouths of silt-laden streams.

Location of Land

The location of the land in relation to the sea in which Kaibab deposition took place was first considered by Newberry⁴³ in his classic report of 1861. Believing that he found sandstone at Grand Canyon in beds represented by limestones farther south, and influenced by an erroneous correlation of the Utah coal deposits (Cretaceous) with the Kaibab, he concluded that the ancient strand line, representing the northern shore of the sea, must have been in southern Utah. Later, Robinson⁴⁴ also suggested a northerly sea margin on the basis of extensive limestones in southern Arizona, then thought to represent a sea floor of comparable age but since shown to be older. As an alternative suggestion, Robinson pointed to the thinning of the Kaibab southward from Kanab Creek as evidence that the sea became more shallow in that direction.

With the accumulation of data it has become apparent to more recent students that the sea in which the Kaibab formation was developed, transgressed from the west. The wide diversity of composition in the formation where found in the Navajo country of northeastern Arizona indicates,

⁴³ J. S. Newberry, *Report upon the Colorado River of the West, explored in 1857-58 by Lieut. J. C. Ives* (Washington: Government Printing Office), pt. 3, Geological report, p. 63, 1861.

⁴⁴ H. H. Robinson, *The San Franciscan volcanic field, Arizona*, U. S. Geol. Surv. Prof. Paper 76, p. 26, 1913.

according to Gregory,⁴⁵ that deposition there was on the outer margin of a littoral zone where conditions were not uniform. Similarly, the type of fossils, the sandy character, and the marked decrease in thickness of the formation toward the northeast in the Circle Cliffs and San Rafael Swell led to the conclusion by Gregory and Moore⁴⁶ that the portion of the sea in southeastern Utah also was neither deep nor far from shore. Disappearance of the formation farther east and its replacement in the stratigraphic column by red shales and sandstones which become increasingly coarse toward the Colorado state border have been referred to by White,⁴⁷ Baker and Reeside,⁴⁸ and others as evidence that continental deposition and the source of much detrital sediment were to be found in that direction.

As a result of the introduction in this paper of a detailed classification of the Toroweap and Kaibab formations, it is apparent that the statements concerning the proximity to shore cited in the preceding paragraph refer only to the Kaibab β member or time of maximum marine advance represented in that formation. At other stages in the history of this and the Toroweap formation the same eastern areas were, for the most part, above sea level and receiving subaerial deposits. Evidence of this fact is found in a comparison of the type of deposits of each member in any particular section. At Desert View in Grand Canyon, for example, the following types of deposit occur in the order listed:

Toroweap γ , cross-laminated red-bed deposits

Toroweap β , extreme margin of limestone deposition

Toroweap α , massive red beds, with fingers of white cross-bedded sandstone

Kaibab β , sandy, near-shore facies of maximum sea advance

Kaibab α , lagoonal limestones and red beds (inferred)

Shape of Strand Line

A feature of the shore line that has been recognized by a few geologists, but has not been fully brought out in the literature, is its eastward curving, in the general neighborhood of Flagstaff, during the time of Kaibab deposition. The east-to-west thickening of the main limestone member in areas north of Flagstaff has received repeated notice, yet the equally significant southward thickening of sections near Winslow and Holbrook remains barely mentioned. It is true that in the former case the westward thickening of the limestone accompanies an almost complete change of fauna and sediments into those of the open sea, whereas south of the Holbrook-Flagstaff line the formation does not extend far enough to show

⁴⁵ H. E. Gregory, *Geology of the Navajo country*, U. S. Geol. Surv. Prof. Paper 93, p. 20, 1917.

⁴⁶ H. E. Gregory and R. C. Moore, *The Kaiparowits region*, U. S. Geol. Surv. Prof. Paper 164, p. 39, 1931.

⁴⁷ David White, *Flora of the Hermit shale, Grand Canyon*, Carnegie Inst. Wash. Pub. No. 405, 1929.

⁴⁸ A. A. Baker and J. B. Reeside Jr., *Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado*, Bull. Amer. Assoc. Petrol. Geol., vol. 13, no. 11, p. 1448, 1929.

whether the case was similar or not. In the writer's opinion, however, there is little reason to doubt that a similar transition into marine conditions originally existed there. The removal of its deposits from the region of central Arizona by later erosion explains why only the near-shore, brackish-water deposits and fossils remain on the eastern Mogollon Plateau today.

Lateral Environmental Change

Because in general the combined Kaibab and Toroweap formations thicken as the Coconino sandstone thins, numerous geologists have adhered to the theory that a lateral gradation of limestone into sandstone occurs from northwest to southeast. In support of this theory, it has been pointed out that Kaibab thinning was not due to extensive erosion, since the upper or α member of this formation is present in almost every section examined.

The writer does not believe that the Toroweap and Kaibab formations grade laterally and uniformly into the Coconino sandstone. Absence of the western phase of the Toroweap formation in northern sections such as those at Circle Cliffs and San Rafael Swell, Utah, and also in some areas such as Walnut and Oak Creek Canyons to the south, suggests that in these areas the Coconino-like sandstones beneath the Kaibab formation probably represent Coconino-like environment which existed to the landward of Toroweap depositional areas. Stratigraphically, then, these deposits are equivalent to the Toroweap. The lateral change from one type of sediment to another, hence the change from one environment to another, was not advanced across the regions but confined essentially to one area, as demonstrated by exposures of the intertongued or "transition" phase of the Toroweap.

Palæogeographic Map

The development of a single palæogeographic map to represent the time of Toroweap and Kaibab deposition is impracticable. In order properly to illustrate the stages of advance and retreat of the seas as represented by the members in these formations, at least six maps are necessary. For this reason reference should be made to the maps showing distribution of facies (figures 7, 22, 23) for an understanding of these conditions.

The present easternmost exposures of the western phase of the Toroweap formation indicate almost precisely the original border of the sea during its maximum advance. The same is only slightly less true of the eastern and northeastern borders of the Kaibab as illustrated by the map of its β member, although in this case present outcroppings are not exposed quite as far as the original shore line. To the south, west, and north, on the other hand, the story is different. The present farthest exposures in any of these directions of sediments of either formation by no means indicate the original limits of the basins of deposition. Indeed, it seems certain from the thickness and character of the sediments and the nature of the

faunas as found in peripheral exposures that the seas once extended much farther in these directions and, as suggested by Longwell, may originally have extended westward "even beyond the present continental border."⁴⁰ Both eastern and northern connections of the sea in which Kaibab sediments were deposited have been suggested on the basis of its fauna. The validity of these correlations, involving the Leonard, Manzano, Chiricahua, and Phosphoria formations, is purely a paleontological question, hence the discussion of the probable relationships is reserved for the chapter on stratigraphy.

CLIMATOLOGY

From general knowledge of the Permian period, it is possible to substantiate views of the climatic record suggested by field studies of the Toroweap and Kaibab formations. Matthew⁴¹ states that the Permian is representative of a time of great uplift resulting in thick, barren formations, general aridity, and development of mountain glaciation, in contrast with the preceding periods of uniform base-leveling which resulted in widespread limestone and coal deposition. Schuchert speaks of it as "a period of continued arid climates"⁴² with marginal shallow sea pans depositing red formations and gypsum. White⁴³ views the climates of Permian time as changing to drier and perhaps warmer summer periods in the northern province, consequent to a changed world landscape and compensated by greater precipitation in the southern or Gondwana province.

In the region of northern Arizona and southern Utah, evidence of Permian conditions, in the form of red beds and a characteristic semi-arid type of flora, is found as low in the stratigraphic column as the "lower part of the Supai formation," according to White.⁴⁴ As the Toroweap and Kaibab formations are considerably above the Supai, and also occur above the Hermit shale and Coconino sandstone, both of which have been shown⁴⁵ to represent times of semi-aridity or aridity, it seems certain that the Toroweap and Kaibab formations were deposited in the midst of a typical northern hemisphere, Permian environment. Correlation of the Kaibab with the Leonard formation of Texas, moreover, places it in the Middle Permian.

Some direct evidence of climatic conditions prevalent during Toroweap and Kaibab deposition is available. The occurrence of warm, dry seasons is indicated by extensive gypsum deposits in the upper member of each

⁴⁰ C. R. Longwell, *The pre-Triassic unconformity in southern Nevada*, Amer. Jour. Sci., 5th ser., vol. 10, p. 109, 1906.

⁴¹ W. D. Matthew, *Climate and evolution*, Ann. New York Acad. Sci., vol. 24, p. 173, 1915.

⁴² Charles Schuchert, in Huntington, *The climatic factor as illustrated in arid America*, Carnegie Inst. Wash. Pub. No. 193, p. 279, 1914.

⁴³ David White, *Some features of the early Permian flora of America*, Rept. U. S. Internat. Geol. Cong., Washington, p. 10, 1904.

⁴⁴ *Ibid.*, p. 2.

⁴⁵ David White, *Flora of the Hermit shale, Grand Canyon*, Carnegie Inst. Wash. Pub. No. 46, 1909; Edwin D. McKee, *The Coconino sandstone—its history and origin*, Carnegie Inst. Wash. Pub. No. 46, VII, 1904.

formation and by gypsum beds at the base of the Toroweap. Other commonly associated features of playa environments such as thin-bedded, chemically precipitated limestones, travertines, and breccias are also numerous, while the red beds themselves testify as to the state of oxidation. Significant also is the sand-dune environment represented by the Coconino-like deposits on the landward margins of the Toroweap, and locally also of the Kaibab formation.

It is not surprising to find the marine invertebrate life of the Toroweap and Kaibab formations little affected by the world-wide climatic changes postulated for the Permian period, and including genera of brachiopods and other groups similar to those of the preceding periods. As explained by Schuchert, "A climatic change naturally must affect the land life more quickly and profoundly than that of the marine waters, for the oceanic areas have stored in themselves a vast amount of warmth that is carried everywhere by the currents."⁵⁵ Also he points out that the surface waters in temperate and tropical regions are the last to be affected, since they are modified only after all the oceanic deeps have been altered by sinking cold waters.

In view of the fact that glaciation is known to have developed extensively in various parts of the world during Permian times, it is thought desirable to discuss next the possibility of a cold climate's having prevailed during the deposition of the Toroweap and Kaibab formations. The following types of evidence have been suggested as pointing to such conditions in this area and at this time: (1) the lack of reef corals, which in certain warm periods, especially the Pennsylvanian, were very abundant; (2) the presence of phosphate beds in the Phosphoria (a formation considered almost if not quite equivalent in time), believed by Mansfield⁵⁶ to be the reflection of a cool climate; (3) glaciation postulated for the late Paleozoic in areas as close as Oklahoma.⁵⁷

Probably the suggestion of glaciation in Oklahoma may be disregarded in this connection since Schuchert⁵⁸ has shown that its presence there is very questionable. Furthermore, Smith has pointed out that "if any effect of glaciation is to be found in the Southwestern States, it must be sought . . . above the Word formation, . . . since the cephalopods show a virtually continuous genetic series from the Pennsylvanian through the Word"⁵⁹ (stratigraphically above the Kaibab-Toroweap).

Concerning the phosphate deposits of Wyoming in relation to the cli-

⁵⁵ Charles Schuchert, in Huntington, *The climatic factor as illustrated in arid America*, Carnegie Inst. Wash. Pub. No. 192, p. 246, 1914.

⁵⁶ G. R. Mansfield, *Geography, geology and mineral resources of part of southeastern Idaho*, U. S. Geol. Surv. Prof. Paper 152, p. 366, 1927.

⁵⁷ S. Weidman, *Was there Pennsylvanian-Permian glaciation in the Arbuckle and Wichita Mountains of Oklahoma?* Jour. Geol., vol. 31, pp. 466-489, 1923; J. A. Taff, *Ice-borne boulder deposits in mid-Carboniferous marine shales*, Bull. Geol. Soc. Amer., vol. 20, pp. 701-702, 1910.

⁵⁸ Charles Schuchert, *Review of the late Paleozoic formations and faunas*, Bull. Geol. Soc. Amer., pp. 836-837, 1928.

⁵⁹ J. P. Smith, *The transitional Permian ammonoid fauna of Texas*, Amer. Jour. Sci., 5th ser., vol. 17, p. 66, 1929.

matic problem of the Toroweap and Kaibab, the writer believes there is little that can be inferred with assurance. In the first place, according to Mansfield, they represent conditions which were local in time and distribution. In the second place, an exact time equivalence between the Phosphoria and the Toroweap-Kaibab sequence is open to question.

The lack of reef corals in the Toroweap and Kaibab limestones, as has been pointed out before in this paper, may readily be explained by increased salinity of the waters or other factors related to the prevailing aridity of the time. It is seen, therefore, that none of the arguments favoring cold climate are very convincing and they are far outweighed by evidences of a warm, dry climate, at least seasonally, with evaporation far in excess of precipitation.

V. PALÆONTOLOGY AND STRATIGRAPHY

In the Toroweap and Kaibab formations of northern Arizona, southern Utah, and Nevada the invertebrate faunas, consisting of many and varied species, have long been known in a general way through the descriptions of Newberry, the stratigraphic work of Shimer, and especially through the numerous faunal lists prepared by Girty and included in publications of the U. S. Geological Survey. Although the distribution of the various types of fossils has not heretofore been determined, it has for a long time been clear that impoverished facies consisting mostly of gastropods and pelecypods and open-sea facies made up largely of brachiopods were both represented in these strata. In the published lists of Girty and others over 80 genera of invertebrates, including 19 of brachiopods, 14 of bryozoa, 15 of gastropods, 22 of pelecypods, and 6 of cephalopods are to be found.

Although the open-sea or marine facies in each of these formations contains abundant fossils, representing several animal groups typical of the Permian, the formations cannot be considered faunally rich when compared with certain others of corresponding age, such as those in west Texas. Ammonoids, fusulinids, and the aberrant brachiopods such as *Lyttonia*, *Scacchinella*, and *Richthofenia* are almost entirely absent, and the fauna contains principally crinoids, horn corals, normal brachiopods, and bryozoa.

The near-shore, "brackish water" facies of the Kaibab and Toroweap formations, as in other regions of Permian sediments, contain impoverished faunas consisting largely of pelecypods and gastropods but with a few cephalopods, scaphopods, and trilobites. Largely because of the local or provincial character of these faunas, and also because of their poor preservation in most instances, their value for broad correlation is relatively slight, and so no attempt to describe them is made here. The brachiopods of the open seas, on the other hand, are largely of species already known from other regions and are usually well preserved, so they are discussed and compared in considerable detail.

References to the attempts at dating and correlating the Kaibab (and Toroweap) formation are essentially those which make up the history of geologic exploration in the Colorado Plateau. From the middle of the nineteenth century, when Jules Marcou and J. S. Newberry made the first studies in this region, through the era of Powell, Gilbert, and Walcott, and on into the early part of the present century, opinion regarding the age of these formations has shifted back and forth between the Permian and the Pennsylvanian.

As recently as 1910 publications have given the age of the Kaibab formation as Pennsylvanian, but since that time there has been almost uniform

agreement on its Permian age. Girty,¹ Schuchert,² Shimer,³ Moore,⁴ and others have all presented in greater or less detail reasons for this conclusion. Furthermore, the validity of the correlation has steadily gained support as knowledge of the fossils in other American Permian sections has increased. Some of the most recent work in this connection has been done by King,⁵ who has indicated that the Kaibab is equivalent to the Leonard formation of the Glass Mountain section, considered to be Middle Permian—a viewpoint substantiated by the detailed studies of Kaibab brachiopods in part II of this monograph.

In this chapter the first part is devoted to a general discussion of the Kaibab and Toroweap fossils—the various kinds represented, their distribution and abundance, and something of their value in correlations. The second part is a discussion of stratigraphic relationships between the Kaibab and Toroweap formations and the Permian strata of adjoining regions, comparing especially the brachiopod faunas.

TYPES OF FOSSILS

Worms

That great quantities of annelid worms once existed in certain of the calcareous oozes and other sediments which covered the sea floor and have since been changed into rocks of the Kaibab formation is suggested by fucoid-like structures in a number of horizons and at many localities. Evidences of burrows, some with the forms of straight tunnels but more with tortuous channels, are usually represented today by the solid matrixes which originally filled them and now stand out in relief on the bottom sides of massive beds.

The most common type of structure among those attributed to the work of boring worms in the Kaibab formation is that illustrated in plate 39. In eastern Grand Canyon sections these are found both in sandstones and in sandy limestones at many horizons in the β member of the formation. From the length, uniform width, and winding pattern of each individual tube, it seems quite certain that the present interpretation of their origin is correct.

Another type of trail found in the Kaibab formation which definitely seems to be due to annelids is seen in plate 40*b*. This long, narrow variety is common in the sandstones at the base of the α member—sediments deposited in very shallow waters, or even above, at the time that the open sea retreated from the area.

¹ G. H. Girty, U. S. Geol. Surv. Bull. 211, pp. 73–83, 1903.

² Charles Schuchert, *On the Carboniferous of the Grand Canyon of Arizona*, Amer. Jour. Sci., 4th ser., vol. 45, pp. 347, 369, 1918.

³ H. W. Shimer, *Permo-Triassic of northwestern Arizona*, Bull. Geol. Soc. Amer., vol. 30, p. 493, 1919.

⁴ R. C. Moore, *Stratigraphy of a part of southern Utah*, Bull. Amer. Assoc. Petrol. Geol., vol. 6, no. 3, p. 210, 1922.

⁵ R. E. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, 1930.

Corals

Although horn corals are fairly numerous in the marine facies of the Kaibab formation (β member, facies 1), the great reef-building corals of the Paleozoic seem to be largely lacking. Shimer⁶ reported *Chatetes milleporaceus* E. & H. as rare in the section at House Rock Valley, and there are no other records of this type of coral. Of the Tetracoralla, Girty lists *Zaphrentis* sp. from Weiser Ridge in northwestern Arizona and *Zaphrentis*? sp. from Beaver Canyon, Utah. He records *Lophophyllum* sp. from Parusi-Wompats Spring north of Shinumo Quadrangle, while Shimer lists *L. profundum* E. & H. as "common" in House Rock Valley and "abundant" 3 miles south of Jacob's Lake, Kaibab Plateau.

One zone or facies that seems to be outstanding so far as its coral fauna is concerned is located near the top of the α member in the Harrisburg dome, southwestern Utah. Girty states⁷ that it contains "a unique fauna" consisting of *Favosites*? n. sp., *Lithostrotion*? n. sp., and *Campophyllum*? n. sp.

Sponges

Sponges of undetermined type are very common in the massive β member limestone of the Kaibab formation, where they form the centers or nuclei for spherical concretions and nodules of chert. The siliceous sponge skeletons are now largely in the form of chalcedony, the surface of an individual varying from a small fraction of an inch to 3 inches and occasionally more. No detailed studies of these sponges have yet been made, but their relationship to the enclosing chert concretions is discussed in chapter III of this paper.

The distribution of the sponges in the Kaibab formation is of considerable interest and significance. They are seldom found outside of the true marine facies except in the borders of adjoining facies. In favorable areas they are abundant both vertically and laterally in the crystalline limestones. They are found to some extent in the sandy limestones, but in the environments represented by the pure sandstones and the dolomites they apparently seldom lived. Sponges are also present, though not extremely numerous, in the marine facies of the Toroweap formation.

Published lists prepared by Dr. G. H. Girty for various U. S. Geological Survey publications have shown the presence of sponges in the following localities and horizons (numbers in parentheses refer to bibliography):

Goodsprings Quadrangle, Nev. Kaibab β ? (32)

1 mi. SW. of Ohio Oil Co. well, Circle Cliffs, Utah. Kaibab β (27)

3 mi. S. of Ohio Oil Co. well, Circle Cliffs, Utah. Kaibab β (27)

Parusi-Wompats Spring, north of Shinumo Quadrangle. Kaibab β (61)

Head of Black Box Canyon, San Rafael, Utah. Kaibab α (20, 49)

⁶ H. W. Shimer, *Permo-Triassic of northwestern Arizona*, Bull. Geol. Soc. Amer., vol. 30, p. 485, 1919.

⁷ G. H. Girty, in Reeside and Bassler, *Stratigraphic sections in southwestern Utah and northwestern Arizona*, U. S. Geol. Surv. Prof. Paper 129, p. 67, 1922.

Crinoids

Crinoids are abundantly represented in the marine limestones, facies 1 in β member, of both the Toroweap and Kaibab formations, and fragments of them are found, at least occasionally, in every other fossil-bearing facies of these formations. Several different species are undoubtedly represented, but only in a few rare instances have more than joints or stem fragments been noted, so no specific or even generic determinations have been attempted to the writer's knowledge.

Because of the remarkably great number of crinoid fragments in parts of facies 1 of the Toroweap limestone, this unit was originally designated as the "crinoidal limestone" by Newberry. Tracing this lithologic unit eastward or shoreward into facies 2, however, the rapidly diminishing numbers and the generally dwarfed character of the crinoids within it testify to the effects of an increasingly unfavorable environment in that direction. Less apparent but equally significant is a corresponding transition eastward to beds with crinoids of impoverished character in the β member of the Kaibab.

Echinoids

The class Echinoidea is represented in the Toroweap and Kaibab formations by several species of *Archæocidaris*. The presence of these fossils was first noted by Newberry, who in 1858 found them "in great numbers in the crinoidal limestone in the upper part of the Carboniferous series on the banks of the Colorado river." He further states that "they are so numerous in some localities that a dozen or more are visible on a square foot of the weathered surface of the rock."⁸

Although no interambulacral plates were found, Newberry described three species of *Archæocidaris* on the basis of spines. These were *A. longispinus*, *A. ornatus*, and *A. gracilis*. Strangely enough, practically no mention of fossils representing this genus is to be found in any of the subsequent extensive literature on the rocks of the Toroweap and Kaibab formations. The only exceptions occur in three of the published faunal lists prepared by Dr. G. H. Girty for publications of the U. S. Geological Survey. Using the name *Echinocrinus* sp., he has shown the presence of this genus in the β member of the Kaibab near the mouth of Grand Wash, in undesignated sections of northwestern Arizona, and 3 miles east of Pinedale.⁹

In the course of recent field work the writer has found specimens of *Archæocidaris* to be locally very common in the β member limestones of both the Toroweap and Kaibab formations. In the former they were noted at Toroweap Valley, along the Hurricane fault scarp in southern Utah, and on the Shivwits Plateau; in the latter they were found common in facies 4 at Miller Canyon, Mack's Crossing, and elsewhere on the Mogollon Plateau,

⁸ J. S. Newberry, *Report upon the Colorado River of the West, explored in 1857-58 by Lieut. J. C. Ives* (Washington: Government Printing Office), pt. 3, Geological report, p. 116, 1861.

⁹ Possibly α member.

and also in facies 1 at Toroweap Valley. No specific determinations were made, but from the locality descriptions given by Newberry, it seems probable that his types were all from the Toroweap formation.

Bryozoa

The class Bryozoa is represented in the open-sea facies of the Toroweap and Kaibab formations—especially of the latter—by many genera and species and by an abundance of individuals; very little attention, however, has yet been given these animals. They appear to be good zone indicators in numerous places where they are found both well preserved and in large numbers. No doubt the difficulties of making specific identifications and the general lack of described Permian forms for comparison are largely responsible for the fact that not a single species has yet been described from either formation. It seems probable that many new species are represented, so an interesting field for study invites future investigators.

The general character of the bryozoan faunas of the Toroweap and Kaibab formations is shown in the numerous faunal lists that have been prepared by Dr. G. H. Girty and published in various reports of the U. S. Geological Survey. In these, specimens are identified only generically. Because in most instances information is given on localities and horizons, however, the bryozoa may be referred without doubt to definite members and facies and therefore the information has greater value than might at first be supposed. These data are briefly summarized in the following paragraphs.

Almost everywhere in facies 1 (open-sea facies) of the β member, Kaibab formation, bryozoa are common. A majority of those listed by Girty unquestionably came from it, so they are given here (numbers in parentheses refer to bibliography): *Fistulipora*, *Meekopora*, *Stenopora*, *Septopora*, *Polypora* from Parusi-Wompats Spring north of Shinumo Quadrangle (62); *Fistulipora*, *Septopora* from Aubrey Cliffs, northwest of Seligman (10); *Stenopora*, *Fenestella*, *Polypora*, *Leioclema*, *Batostomella* from localities in extreme northwestern Arizona (73); *Fistulipora*, *Leptopora*, *Phyllopora*, *Cystodictya* from Grand Wash Cliffs, 4 miles southeast of Bronze-L mine (44); *Batostomella* from fault block near mouth of Grand Wash and from Weiser Ridge, 2 miles south of Narrows (44); *Fistulipora*, *Septopora* from Beaver Canyon, Utah (38).

Other data pertaining to the bryozoa of facies 1 (and also facies 2) of this member of the Kaibab formation have been kindly furnished by Mr. David Keppel. He made a preliminary study in 1931–1932 of the Kaibab species, based on thirty specimens from localities in eastern Grand Canyon. The results of this work have been made available to the writer through his courtesy. Furthermore, illustrations of the Grand Canyon material shown on plate 41 were kindly furnished by him.

Although Mr. Keppel made no attempt to describe any of the new specimens in the collection from Grand Canyon National Park which he studied,

the material was carefully worked out as to genera and assigned to species where such were already described. He concluded that six genera and eight species were represented among the thirty specimens, but that of these, only three species had already been described. The forms recognized and discussed by him are as follows: *Fistulipora* n. sp.; *Meekopora* n. sp.; *Stenopora* no. 1, n. sp.; *Stenopora* no. 2, n. sp.; *Polypora spinulifera* Ulrich; *Septopora biserialis* (Swallow); *Septopora* no. 2, n. sp.; *Rhombopora lepidodendroides* Meek.

Eastward in the β member of the Kaibab formation, in what is probably facies 2 (House Rock Valley), bryozoa were collected by Shimer (77) and identified by him as *Septopora biserialis* Swallow. Still farther east and north in this member, in facies 5 (Circle Cliffs, Utah), other bryozoa have been collected. They were found in beds that are interesting because they contain a mixture of brachiopods and mollusks. From this assemblage Girty (27) lists *Septopora*, *Phyllopora*, *Schizophoria*, and *Fenestella*.

In the thin, "lagoonal" limestones of the α member of the Kaibab formation, faunas are almost entirely molluscan, but occasionally a brachiopod or bryozoan is found. Especially are these classes represented in the limestones of facies 1 in northwestern Arizona. Here Reeside and Bassler (73) collected the following genera, identified by Girty: *Batostomella*, *Polypora*, *Phyllopora*.

In the Toroweap formation, bryozoa are known to be fairly abundant in association with the brachiopods of the open-sea facies (β member, facies 1), yet few have been collected and studied. The only published list to include bryozoa from this limestone is that of the fauna of Goodsprings Quadrangle, Nevada (32). Unfortunately one cannot be certain that all the genera listed in this are from the Toroweap and not from the overlying Kaibab, since Hewitt merely states that "most of the species came from the upper portion of the lower limestone member." The genera given are the following: *Amplexus*, *Fistulipora*, *Stenopora*, *Leioclema*, *Fenestella*, *Polypora*, *Septopora*, and *Phyllopora*.

Brachiopods

Particular attention has been given to brachiopods in this study—far more than to any other class of animals—because in the Toroweap and Kaibab formations they constitute the most useful group for broad correlation purposes. Not only are they usually abundant and for the most part well preserved, hence easy to study in detail, but also they are largely representative of the open seas, so are cosmopolitan in character. Indeed, many of the forms appear to be absolutely identical even where found thousands of miles apart. It should also be pointed out that the Permian brachiopods of other regions have been more completely described than have other Permian fossils, so data for comparison are more readily available.

Brachiopods are found in many parts of the Toroweap and Kaibab formations and this class is represented not only by an abundance of indi-

viduals but also by a fairly large number of genera and species. The principal areas of brachiopod distribution, each of which contains a rather distinctive assemblage, are facies 1 (open-sea facies) of the Toroweap β member, facies 1 (open-sea facies) of the Kaibab β member, facies 5 (a near-shore facies) of the Kaibab β member, and facies 1 (a lagoonal facies) of the Kaibab α member. In all other members and facies of these formations, brachiopods are nearly or entirely absent.

The brachiopods of facies 1 in the massive limestone of the Kaibab formation represent by far the best-known assemblage in the Permian of the Colorado Plateau area. They constitute the *Productus bassi* fauna, so called because of the large and extremely abundant productid of that name that is found throughout. Most of this fauna has been described and illustrated in part II of this monograph, where it is shown to contain at least twenty-three species and fifteen genera. Four or more additional genera are represented in published faunal lists covering the Kaibab formation, so there can be no doubt concerning the richness of the fauna. It is true that it does not contain any of the characteristic aberrant fossils of the Permian such as *Lyttonia* or *Prorichthofenia*, but nearly all the normal brachiopod types of this period are represented.

Facies 1 of the Toroweap limestone contains brachiopods of the same general character as those in facies 1 of the β member, Kaibab. Considering the rather similar environments and the evidence that only a brief interval separated them, this is to be expected. Just how much the faunas actually differ, however, is not at present known, since fossils are usually difficult to collect from the Toroweap and have not yet been studied in detail. There appear to be fewer species and, from what is known, it seems probable that these differ in detail from corresponding Kaibab species. Two brachiopods from the Toroweap β fauna are described in part II, and one of these, *Productus ivesi*, by its abundance shows that this is the true *Productus ivesi* fauna, a name erroneously applied in the literature to the fossils of the massive limestone in the Kaibab formation.

In southeastern Utah, in rocks that are generally correlated with the Kaibab formation and are in this paper tentatively assigned to facies 5 of the Kaibab β member, brachiopods are numerous. These are interesting both because of their general dissimilarity to those in facies 1 and because of their usual association with mollusks of many species, a feature not found in the other brachiopod groups discussed. This fauna is not yet well known and is difficult to study because of poor preservation and inaccessibility of localities. The two most common species, *Spirifer pseudocameratus* and *Waagenoconcha montpelierensis*, are described and illustrated in part II of this monograph, and two others, *Squamularia* sp. and *Pustula nevadensis*, are illustrated. From the Circle Cliffs, Utah, outcrops, Girty lists four additional species of brachiopods, but these do not include the most common forms of the Kaibab open-sea facies. In brief, the similarity of this fauna to the highly specialized one of the Phosphoria formation and

the association of the brachiopods with mollusks of the common near-shore or lagoonal types suggest an environment of unusual character.

One other facies which contains numerous brachiopods is facies 1 of the Kaibab α member. Apparently, as the seas retreated following the invasion in which the massive limestones of the Kaibab were formed, certain brachiopods remained in abundance in the relict embayments or lagoons which were located on the seaward margins of the region. Even in some limestone beds immediately above or below gypsum deposits in this area, these brachiopods are found to have persisted. In published faunal lists Girty has shown nine species and as many genera from the area of northwestern Arizona and southwestern Utah. The most common species found are *Composita* sp., *Dielasma phosphoriensis*, and *Chonetes* sp. Commonly associated with these brachiopods are mollusks of "brackish water" types such as *Euomphalus*, *Schizodus*, and *Bellerophon*.

Except in the instance just cited, the facies of the Kaibab and Toroweap formations which were formed at times other than those of maximum marine advance are characterized by either a paucity or a total lack of brachiopods. The same is true of the near-shore facies of the marine members. It is clearly evident, therefore, that the brackish or, in some instances, highly saline character of the local environments was not favorable to the development of brachiopods. The following summary gives evidence in support of this theory:

Toroweap:

- γ member No fossils known
- β member, facies 2 A few *Productus ivesi*, only brachiopod
- α member, facies 1 and 2 No brachiopods known

Kaibab:

- γ member No brachiopods known
- β member, facies 2*Productus bassi*, *Chonetes kaibabensis* scarce,
a few other brachiopods in western part
- β member, facies 3 No brachiopods known
- β member, facies 4*Productus bassi* scarce, only brachiopod
- α member, facies 2 and 3*Productus bassi*, *Chonetes* sp. scarce
- α member, facies 4*Productus bassi* scarce, only brachiopod

Pelecypods

Pelecypods are present in every fossil-bearing facies in both the Kaibab and Toroweap formations, and only in the marine limestones are they comparatively scarce. In these marine facies (no. 1 of each formation) they are represented exclusively by members of the pecten group.

The only information available at present on the pelecypods of the Toroweap formation is a list of the genera collected by G. E. Sturdevant from the limestone along the Kaibab Trail and identified by Dr. G. H. Girty. This list shows the following eight genera, most of which appear to be represented by dwarfed forms: *Edmondia*, *Solenomya*, *Nucula*, *Schizodus*, *Pteria*, *Pleurophorus*, *Allorisma*, *Leda*.

The Kaibab formation contains at least twenty-two genera of pelecypods, judging by the faunal lists prepared by Girty and Shimer and published in various papers. A summary of the types of pelecypods and their distribution as indicated in these lists follows (numbers in parentheses refer to bibliography):

- Head of Black Box of San Rafael River. Kaibab β , facies 5 (20)
Edmondia aff. *E. gibbosa* *Aviculopecten* sp.
Parallelodon sp. *Lima*? sp.
Schizodus sp. *Myalina* aff. *M. perattenuata*
- Head of Black Box of San Rafael River. Kaibab α , facies 5 (20)
Nucula levatiformis *Pleurophorus*? sp.
Leda obesa? *Anatina*? sp.
Schizodus? sp.
- 3 mi. S. of Ohio Oil Co. well, Circle Cliffs. Kaibab β , facies 5 (27)
Parallelodon aff. *P. politus* *Myalina* aff. *M. swallowi*
Parallelodon aff. *P. sangamonensis* *Schizodus* (several sp.)
Acanthopecten coloradoensis *Astartella* aff. *A. concentrica*
Pernipecten sp. *Astartella* aff. *A. varica*
Deltopecten aff. *D. occidentalis* *Myoconcha*? sp.
Aviculopecten (several sp.) *Pleurophorus* aff. *P. occidentalis*
Pseudomonotis (several sp.) *Pleurophorus* sp.
- 3 mi. S. of Ohio Oil Co. well, Circle Cliffs. Kaibab β , facies 5 (27)
Deltopecten aff. *D. occidentalis* *Pseudomonotis*? sp.
Aviculopecten (several sp.) *Pleurophorus*? sp.
- Yellow cone, east side of Circle Cliffs. Kaibab β , facies 5 (27)
Acanthopecten coloradoensis *Pleurophorus*? sp.
Astartella sp.
- 1 mi. SW. of Ohio Oil Co. well, Circle Cliffs. Kaibab β , facies 5 (27)
Edmondia aff. *E. ovata* *Myalina* aff. *M. swallowi*
Nucula? sp. *Astartella* aff. *A. concentrica*
Parallelodon? sp. *Myoconcha*? sp.
Aviculopecten (2 sp.) *Pleurophorus* aff. *P. occidentalis*
Pseudomonotis aff. *P. hawni* *Pleurophorella*? sp.
- 3 mi. S. of Ohio Oil Co. well, Circle Cliffs. Kaibab β , facies 5 (27)
Edmondia aff. *E. gibbosa* *Myoconcha*? sp.
Pernipecten? sp. *Astartella*? sp.
Lima sp. *Pleurophorus* aff. *P. occidentalis*
- Sections in northwestern Arizona and southwestern Utah. Kaibab α , facies 1 (73)
Nucula levatiformis *Pseudomonotis*? sp.
Leda obesa *Myalina* aff. *deltoidea*
Aviculopecten? sp. *Schizodus wheeleri*
Pteria (Bakewellia)? sp. *Pleurophorus mexicanus*
- In California Ridge, 2 mi. S. of Muddy Creek. Kaibab β , facies 1 (44)
Acanthopecten coloradoensis
- Parusi-Wompats Spring, N. of Shinumo Quadrangle. Kaibab β , facies 1 (62)
Aviculopecten (2 sp.) *Pseudomonotis* aff. *P. hawni*
Acanthopecten occidentalis

- Rim of Little Colorado Canyon, 5 mi. above mouth. Kaibab α , facies 2 (25)
Bakewellia or *Pteria* sp. *Allorisma?* sp.
Schizodus? sp. *Pleurophorus?* sp.
- 3 mi. E. of Pinedale, Ariz. Kaibab $\beta?$, facies 4 (10)
Edmondia sp.? *Schizodus wheeleri*
Cardiomorphia? sp. *Pleurophorus* sp.
Nucula levatiformis
- Near Pinedale, Ariz. Kaibab $\beta?$, facies 4 (82)
Schizodus aff. *S. affinis* *Pteria* or *Bakewellia* sp.
- Goodsprings Quadrangle, Nevada. Kaibab or Toroweap β , facies 1 (32)
Deltopecten coreyanus *Acanthopecten coloradoensis*
Deltopecten aff. *D. mccoysi* *Pseudomonotis* sp.
- 2 mi. S. of Flagstaff, Ariz. Kaibab $\alpha?$, facies 3 (77)
Allorisma terminale
- Walnut Canyon, Ariz. Kaibab $\alpha?$, facies 3 (77)
Pinna sp.
- Hance Trail, Grand Canyon. Kaibab β , facies 3 (77)
Bakewellia parva *Astartella gurleyi*
- House Rock Valley, Ariz. Kaibab β , facies 2 (77)
Aviculopecten occidentalis? *Aviculopecten coloradoensis*
- 3 mi. S. of Jacob's Lake, Ariz. Kaibab β , facies 2 (77)
Aviculopecten occidentalis *Aviculopecten coloradoensis*
- Hurricane Cliff, S. of Virgin River. Kaibab β , facies 1 (77)
Aviculopecten coloradoensis

Scaphopods

Scaphopods are very numerous in every near-shore or "brackish water" facies of the Kaibab and Toroweap formations, associated with the common genera of pelecypods and gastropods typical of the nonmarine environments. Because they are almost invariably preserved as either internal or external molds and possess few distinguishing characteristics, specific identification is usually unsatisfactory. Only in facies 2 (Point Sublime) and facies 4 of the Kaibab α member have silicified specimens been noted by the writer.

In the published faunal lists of the U. S. Geological Survey prepared by Dr. G. H. Girty and in those of Shimer, specimens have been referred to *Plagioglypta canna* White. They represent localities and horizons as follows (numbers in parentheses refer to bibliography):

- Red (Hance) Canyon, Grand Canyon. Kaibab, $\alpha?$ member, facies 2 (77)
 Localities in northwestern Arizona. Kaibab, α member, facies 1 (73)
 3 mi. S. of Ohio Oil Co. well, Circle Cliffs. Kaibab, $\beta?$ member, facies 5 (27)
 3 mi. E. of Pinedale, Ariz. Kaibab, $\alpha?$ member, facies 3 (10)
 Black Box, San Rafael Swell, Utah. Kaibab, α member, facies 5 (20, 49)

Reference to measured sections in this paper will show the presence of these scaphopods in many other localities and horizons, though they appear to be entirely absent from the marine facies of both formations.

In addition to the smooth-surfaced, straight scaphopods of the Kaibab and Toroweap formations, others occur not uncommonly which are also straight and tapering but which have numerous longitudinal costæ. They are closely similar to if not identical with the species described by Girty¹⁰ as *Dentalium mexicanum* from the San Andres formation of New Mexico. In internal molds, it is, of course, impossible to distinguish this *Dentalium* from *Plagioglypta*, but enough silicified specimens and external molds have been discovered to show that in most facies these two types are associated.

Gastropods

The gastropods of the Toroweap and Kaibab formations, like most of the other mollusks, are confined to the near-shore, brackish-water and highly saline facies. Though fairly common in many localities and horizons, they are for the most part poorly preserved, remaining in the form of molds, so specific determination is usually difficult if not impossible. In most places members of the *Bellerophon* group, especially *Bucanopsis* and *Euphemus*, appear to be the most numerous. These caused the early geologists in the region to give the name "*Bellerophon* limestone" to the uppermost member (α) of the Kaibab. The next most abundant gastropods are the *Euomphalidæ* and *Pleurotomariidæ*.

In the Toroweap formation, the near-shore, magnesian limestone facies (no. 2) abounds in mollusks of many types, most of which appear to be definitely dwarfed. A collection from this limestone, made along the Kaibab Trail of Grand Canyon in 1928 by G. E. Sturdevant and identified by Dr. G. H. Girty, included the following five genera of gastropods: *Naticopsis*, *Goniospira*, *Aclisina*, *Bellerophon*, and *Euphemus*. These are the only gastropods yet recorded from the Toroweap.

In the Kaibab formation gastropods are found in most of the facies. Generally they are less numerous and varied than the associated pelecypods, but in facies 4 of the α member they are extremely abundant and far outnumber all other forms. In this area *Pleurotomaria* is especially common, and is represented by several species. *Euphemus*, *Bellerophon*, *Naticopsis*, and others are also fairly common, and as all are silicified, opportunities for detailed study are excellent.

Many gastropods have been collected from facies 2 of the α member at Grand Canyon village. From this highly fossiliferous area the following gastropods are recognized: *Bellerophon majusculus*, *Goniospira* sp., *Euomphalus* sp., *Euphemus* sp., *Pleurotomaria* sp., *Naticopsis* sp.

One uncommon but interesting species of gastropod from the Kaibab formation which has recently been described¹¹ is *Conularia kaibabensis*. The type specimens are from the Kaibab β member on the Kaibab Plateau.

¹⁰ W. T. Lee and G. H. Girty, *The Manzano group of the Rio Grande Valley, New Mexico*, U. S. Geol. Surv. Bull. 389, p. 95, 1909.

¹¹ Edwin D. McKee, *A Conularia from the Permian of Arizona*, Jour. Paleontol., vol. 9, no. 5, pp. 427-429, 1935.

In order to indicate the general distribution and variety of gastropods in other members and facies of the Kaibab formation, a summary of those that have been identified by Girty and others and published in faunal lists follows (numbers in parentheses refer to bibliography) :

- Head of Black Box of San Rafael River. Kaibab α , facies 5 (20)
Bucanopsis modesta *Sphaerodoma* sp.
Euphemus subpapillosus
- 3 mi. S. of Ohio Oil Co. well, Circle Cliffs. Kaibab β , facies 5 (27)
Bucanopsis aff. *B. modesta* *Pleurotomaria* (several sp.)
Euphemus sp.
- 1 mi. SW. of Ohio Oil Co. well, Circle Cliffs. Kaibab β , facies 5 (27)
Euphemus sp.
- 3 mi. S. of Ohio Oil Co. well, Circle Cliffs. Kaibab β , facies 5 (27)
Pleurotomaria sp. *Aclisina* sp.
- Sections in northwestern Arizona and southwestern Utah. Kaibab α , facies 1 (73)
Bellerophon majusculus *Goniospira* sp.
Bucanopsis aff. *B. bella* *Naticopsis?* sp.
Euphemus sp. *Euomphalus* sp.
Pleurotomaria sp. *Platyceeras* sp.
- Black Box Canyon, San Rafael Swell, Utah. Kaibab α , facies 5 (49)
Bellerophon sp. *Warthia?* sp.
Patellostium aff. *P. nodicostatum* *Pleurotomaria?* sp.
Euphemus subpapillosus *Macrochilina?* sp.
- Rim of Little Colorado Canyon, 5 mi. above mouth. Kaibab α , facies 2 (25)
Euphemus sp.
- 3 mi. E. of Pinedale, Ariz. Kaibab $\beta?$, facies 4 (10)
Euphemus sp. *Goniospira?* sp.
- Near Pinedale, Ariz. Kaibab $\beta?$, facies 4 (82)
Schizostoma? sp.
- Hance Trail, Grand Canyon. Kaibab β , facies 3 (77)
Murchisonia? cf. *terebra* *Euphemus* cf. *carbonarius*

Cephalopods

The scarcity of cephalopods in general and the almost complete absence of ammonoids in particular are striking features of the Kaibab-Toroweap faunas. Six nautiloid and one ammonoid genera have been recognized in these formations, but most of them are represented by only one or by very few specimens.

In magnesian limestones, probably referable to the α member of the Kaibab, Marcou claimed in 1858 to have recognized a *Nautilus*, partly on the basis of which he suggested the Permian age of these rocks. A few years later, however, Newberry¹² took exception to the value of this fossil for correlation.

¹² J. S. Newberry, *Report upon the Colorado River of the West, explored in 1857-58 by Lieut. J. C. Ives* (Washington: Government Printing Office), pt. 3, Geological report, p. 72, 1861.

A second early reference to a cephalopod is by G. K. Gilbert, who listed *Orthoceras* from the "Lower Limestone," presumably the Toroweap, of the Aubrey Cliffs. This record is of interest as the only one published of a cephalopod from this formation. Recently, however, the writer has found several specimens of *Domatoceras*? in the Toroweap β along the Kaibab Trail of Grand Canyon.

The following cephalopods from the Kaibab have been recognized by Girty and included in faunal lists of various U. S. Geological Survey publications (numbers in parentheses refer to the bibliography):

- Metacoceras* sp. 7 mi. E. of St. George, Utah. Kaibab α (73)
- Nautilus* sp. 1 mi. SW. of Ohio Oil Co. well, Circle Cliffs. Kaibab β ? (27)
- Nautilus* sp. Not specified, northwestern Arizona. Kaibab α (73)
- Coloceras* sp. San Rafael Swell, Utah. Kaibab α (49)
- Gastrioceras* sp. San Rafael Swell, Utah. Kaibab α (49)
- Foordiceras*? sp. 3 mi. E. of Pinedale, Ariz. Kaibab β ? (10)
- Orthoceras*? sp. 3 mi. S. of Ohio Oil Co. well, Circle Cliffs. Kaibab β ? (27)
- Orthoceras*? sp. San Rafael Swell, Utah. Kaibab α (49)

Other records of cephalopods are from the α member of the Kaibab formation at Grand Canyon village, where the writer has collected several specimens of a large nautiloid identified by Dr. Girty¹³ as *Domatoceras simplex* Hyatt and a few of *Orthoceras* sp.

Crustaceans

The not uncommon and widespread presence of trilobite trails and skeletal fragments in the shallow-water facies of the Kaibab formation testifies to the former abundance of these crustaceans in near-shore and lagoonal areas during Middle Permian times. Many trails that are found in the sandstones at the base, and some higher in the α member of the formation, are well preserved and distinct (plate 40). The animals themselves are represented almost entirely by phygidia, although occasionally part of a cephalon is found. These fossils are most numerous in the thin-bedded, magnesian limestones of the α member, but are not confined to them.

Trilobite specimens from the Kaibab formation were formerly all referred to the genus *Phillipsia*; more recently to *Griffithides*. In some published lists of the U. S. Geological Survey specimens have been specifically identified as *Griffithides scitulus* (Meek and Worthen). According to the recent reclassification of Carboniferous trilobites by Weller,¹⁴ in which use of the names *Phillipsia* and *Griffithides* is restricted, these Permian forms belong to the genus *Ditomopyge*, and the common Kaibab species therefore should be known as *Ditomopyge scitulus*. Probably other species also are present, but poor preservation makes study of these forms difficult.

¹³ G. H. Girty, personal communication, November 27, 1926.

¹⁴ J. Marvin Weller, *Carboniferous trilobite genera*, Jour. Paleontol., vol. 10, no. 8, pp. 704-714, 1936.

The general distribution, by localities and horizons, of trilobites in the Kaibab formation is shown by the following list of specimens that have been examined by the writer in collections or have been included in published lists. In the case of the latter, reference is given in each instance by bibliography number.

Kaibab formation, β member:

Facies 1, Fossil Mountain in Grand Canyon, basal sandy limestone (Grand Canyon col.)

Facies 1, Kanab Canyon, listed as "lower part" (U. S. Geol. Surv. col.)

Facies 5, Circle Cliffs, Utah, 2 localities and horizons (27)

Kaibab formation, α member:

Facies 1, Grand Wash Cliffs, Bronze-L mine, possibly top of β member (44)

Facies 2, Shinumo Canyon, in Grand Canyon (U. S. Geol. Surv. col.)

Facies 2, Grand Canyon village, rather common (Grand Canyon col.)

Facies 3, Bottomless Pit near Flagstaff (Mus. N. Ariz. col.)

Facies 4, Rimey Jim's, between Flagstaff and Cameron (Grand Canyon col.)

Facies 5, head of Black Box Canyon, San Rafael Swell (20)

No trilobites have yet been recorded from the Toroweap formation, but in limestone of its β member ostracods were collected by G. E. Sturdevant. These crustaceans, associated with mollusks in every case, were found along the Kaibab Trail at four horizons. They were reported by Dr. G. H. Girty, who examined this fauna.

Fish

The remains of fish appear to be relatively rare in the Toroweap and Kaibab formations. As a matter of fact, none has yet been reported from the Toroweap and only a few from the Kaibab.

In the Permian collection of the U. S. Geological Survey, which the writer was recently privileged to examine, three fish specimens were noted—one of a tooth and the other two of plates—all collected from Mangum Spring, Shinumo Canyon, in 1882 by C. D. Walcott. Judging from the associated fauna, these came from the α member of the Kaibab formation.

In the fine-grained sandstone of facies 3 in the β member of the Kaibab formation, the writer in 1934 found a shark's tooth (see plate 15). This was examined by Dr. L. Hussakof,¹⁵ of the American Museum of Natural History, who identified it as *Deltodus mercurii* Newberry. According to Branson this species is not known above the Pennsylvanian in the Mississippi Valley, therefore he¹⁶ at first considered the lower Embar of Wyoming, which contained it, as Carboniferous in age.

Recently Branson has revised his opinion concerning the stratigraphic significance of *Deltodus mercurii*, stating that "since other evidence shows that the Phosphoria is a single Permo-Carboniferous unit, the shark is be-

¹⁵ L. Hussakof, personal communication, March 8, 1934.

¹⁶ E. B. Branson, *The lower Embar of Wyoming and its fauna*, Jour. Geol., vol. 24, pp. 639-664, 1916.

lieved to have a longer range than that previously established."¹⁷ Obviously its presence in the Kaibab formation can be interpreted only as indicating a still greater extension of the known range of the species, as the testimony of associated invertebrates and of underlying flora clearly establishes a Middle Permian age.

No other specimens of fish from the Kaibab formation are known to the writer at the present time.

COMPARISON OF THE TOROWEAP AND KAIBAB FAUNAS

As early as 1861 J. S. Newberry, geologist of Lieutenant Ives' exploring expedition, called attention to the two great limestone units near the top of Grand Canyon and briefly discussed the character of their faunas. The upper or "Cherty limestone," as he called it, was shown to be separated from the lower or "Crinoidal limestone" by about 200 feet of other sediments and to have marked differences in lithology. He further stated¹⁸ that although each contained some fossils peculiar to itself, these limestone units had many species in common. On the basis of this evidence Newberry believed the Toroweap and Kaibab formations to represent the Lower and the Upper Carboniferous, respectively.

Considering the difficulties and hazards under which Newberry worked, it is rather remarkable that he was able to make even a preliminary study and comparison of the faunas of the Toroweap and Kaibab formations, yet today, seventy-five years later, our knowledge concerning these faunas and their contrasts alters his concepts of the relationship but little. As typical of the Cherty (Kaibab) limestone, Newberry lists¹⁹ *Productus semireticulatus* (= *P. bassi*), *P. occidentalis*, *Spirigera subtilita* (= *Composita subtilita*), *Orthisina umbraculum* (= *Derbya crassa*), *Rhynchonella uta* (= *Pugnoides uta*), and *Spirifer lineatus* (= *Squamularia guadalupensis*). From the Crinoidal (Toroweap) limestone he reports *Productus ivesi*, *Archæocidaris* and *Spirigera* (= *Composita*). In addition to these he mentions elsewhere the genera *Rhynchonella*, *Orthisina*, and *Spirifer* as typical of this limestone.

It was the intention of the writer to include in this paper the results of a critical analysis and comparison of the brachiopod faunas of the Kaibab and Toroweap formations. Insufficient material from the latter and the pressure of other work, however, have made it necessary to postpone such a detailed study. For the present, therefore, it can be said with assurance only (1) that these faunas are similar in general; (2) that corresponding forms are at least varietally and many even specifically different; (3) that the Kaibab contains a greater variety and abundance of brachiopods than the Toroweap in all areas examined by the writer.

¹⁷ E. B. Branson, *Carboniferous stratigraphy of Wyoming*, (abstract) Proc. Geol. Soc. Amer., p. 392, 1935.

¹⁸ J. S. Newberry, *Report upon the Colorado River of the West, explored in 1857-58 by Lieut. J. C. Ives* (Washington: Government Printing Office), pt. 3, Geological report, p. 60, 1861.

¹⁹ *Ibid.*, pp. 62, 63.

A specific case of comparison between closely related brachiopod forms in these two formations is that between *Productus ivesi* of the Toroweap and *P. bassi* of the Kaibab.²⁰ Another is between *Composita arizonica* of the Kaibab and those Toroweap forms that have been discussed as varieties of it. A third comparison which may be mentioned is between *Squamularias*. Those in the Kaibab appear to be typical *S. guadalupensis*, while specimens from the Toroweap at Grand Wash which have been examined by the writer apparently differed in being more elongate and in having a sinus. Related forms of *Meekella*, *Chonetes*, and other genera represented in both formations have not yet been compared, so further discussion of this subject must await the results of detailed study.

TWO MARINE ASPECTS OF THE KAIBAB

In the Kaibab formation two distinct marine facies (nos. 1 and 5 of the β member) are present. Because the brachiopod faunas of these show little similarity, a discussion of their significance seems desirable.

Facies 1 of the Kaibab formation is the normal marine facies which contains the "*Productus bassi* fauna." The species in it are nearly all represented in the Middle Permian strata of west Texas as is shown in the comparison between the formations of these areas, so the two seas almost surely had direct connection.

Facies 5 of the Kaibab formation has a mixed brachiopod and molluscan fauna. The former is composed chiefly of species well known from the Phosphoria formation to the north. *Spirifer* (*Neospirifer*) *pseudocameratus* and *Waagenoconcha montpelierensis* are abundant and *Pustula nevadensis* fairly common in the Kaibab of this facies and are likewise numerous in the Phosphoria, notably in the *Pustula* member, where they are present together. A *Squamularia* and a *Composita* are also found in the facies 5 Kaibab and are probably the same as members of these genera that are found in the Phosphoria.

Of the three most common and diagnostic brachiopod species from facies 5 of the Kaibab, only one, *Waagenoconcha montpelierensis*, has been found in facies 1 and it is not very common there. From Circle Cliffs in the southern part of this area, however, Girty²¹ has reported two other species which probably are the same as facies 1 forms. These are *Marginifera* aff. *popei* and *Chonetes hillanus* (compare *C. subliratus*). *Composita* and *Squamularia* may also be represented by identical forms in both facies.

Facies 1 and facies 5 of the Kaibab have long been correlated by workers in the region both on the basis of stratigraphic position and of faunas. From the discussion above, however, it is apparent that the faunas do not contribute very substantial evidence, since one has a Texan and the other a Phosphoria aspect with only a few forms in common. These common species, however, are thought by the writer to represent the results of a

²⁰ See under systematic descriptions of these species in part II of this paper.

²¹ G. H. Girty, in Gregory and Moore, *The Kaiparowits region*, U. S. Geol. Surv. Prof. Paper 164, p. 42, 1931.

mingling of forms which have come from different seas with distinct environments. Furthermore, it is suggested that the peculiar environment represented by the northern or Phosphoria sea must have been the cause for the imperfect mixing of species in both areas.

Further discussion of the relationship between the two marine facies of the Kaibab will be given in the comparison between the Kaibab and Phosphoria formations.

COMPARISON WITH THE WEST TEXAS PERMIAN

Inasmuch as "the thickest and most complete section" of Permian rocks in this continent is found, according to King,²² in the area which includes the Glass Mountains, the Delaware-Guadalupe Mountains, and the Diablo Plateau of western Texas and eastern New Mexico, and as most of the beds in the Glass Mountains represent normal marine facies, it is logical that this be considered a "standard" North American Permian section.²³ From the standpoint of determining the stratigraphic position and age of the Kaibab formation, therefore, a comparison of its faunas with those of the Permian marine beds of Texas is practically essential. Fortunately the brachiopods of that area are already well known through the works of Shumard, Girty, King, and others.

The literature on the Permian period contains many references that suggest relationships between the Kaibab formation and various west Texas deposits. Earlier correlations naturally were of a general nature. In 1910 Girty²⁴ stated that "the Aubrey group of Arizona, rather widely distributed," was one of "the more important of the facies provisionally referred to the Hueconian."²⁵ A few years later, in discussing the Kaibab formation, he²⁶ tentatively correlated it with the upper part of the "Hueco formation" of western Texas, and stated that consequently even though it contained a number of species that were very similar to or identical with those that were found in the Guadalupian fauna, it must be older than the Guadalupian group above the "Hueco."

Numerous later publications²⁷ have described the Kaibab formation as

²² P. B. King and R. E. King, *Stratigraphy of outcropping Carboniferous and Permian rocks of trans-Pecos Texas*, Bull. Amer. Assoc. Petrol. Geol., vol. 13, no. 8, p. 920, 1929.

²³ The Permian section of central and northwestern Texas including the Wichita, Clear Fork, and Double Mountain formations has been used as a "tentative, non official" standard for the United States by J. S. Williams, *Stratigraphic nomenclature in the United States*, XVIth Internat. Geol. Cong., Guidebook 29, 1932.

²⁴ G. H. Girty, *Outlines of geologic history* (Chicago: Univ. of Chicago Press), p. 130, 1910.

²⁵ The name "Hueco" is no longer in common use. The Hueco limestone of Richardson has been divided into a large number of different stratigraphic units of Mississippian, Pennsylvanian, and Permian age.

²⁶ G. H. Girty, in L. F. Noble, *The Shinumo Quadrangle, Grand Canyon district, Arizona*, U. S. Geol. Surv. Bull. 549, p. 71, 1914.

²⁷ See E. C. Case, *The environment of vertebrate life in the late Paleozoic in North America: a paleogeographic study*, Carnegie Inst. Wash. Pub. No. 283, pp. 113, 259, 1919.

having been deposited in a great seaway extending from trans-Pecos Texas and adjacent portions of Mexico and New Mexico, westward into Arizona, thence northward through the Basin Province into Alaska. More detailed correlation, however, has awaited the work of King,²⁸ who, by describing the brachiopod fauna of the Glass Mountains, was able to show a close relationship between the Leonard and Kaibab faunas. His conclusions were that although a few Kaibab species are not known in the Texas area, and even though others are found as high as the Capitan or as low as the Wolfcamp, it seemed evident from the abundance of *Productus bassi* in both Kaibab and Leonard formations, and from the great number of other species common to both formations, that they are equivalent in age.

The systematic description of Kaibab brachiopods included in part II of this monograph makes possible a critical analysis and comparison of faunas from the Arizona and Texas Permian sections under discussion. In table 15 have been listed the 21 brachiopods that have been specifically

TABLE 15. COMPARISON OF BRACHIOPODS OF KAIBAB AND OF GLASS MOUNTAIN PERMIAN

Species	Kaibab	Glass Mountain		
		Hess	Leonard	Word
<i>Rhipidomella transversa</i> King.....	X	X	X	...
<i>Meekella pyramidalis</i> (Newberry).....	X	..	Aff.	...
<i>Derbya nasuta</i> Girty.....	X	X	X	X
<i>Derbya regularis</i> McKee.....	X	..	....	Aff.
<i>Chonetes kaibabensis</i> McKee.....	A	..	....	X
<i>Chonetes</i> (<i>Lissochonetes</i>) <i>subliratus</i> Girty.....	A	X	A	X
<i>Productus</i> (<i>Dictyoclostus</i>) <i>bassi</i> McKee.....	A	X	A	?
<i>Productus</i> (<i>Dictyoclostus</i>) <i>occidentalis</i> Newberry.....	A	..	A	X
<i>Productus</i> (<i>Dictyoclostus</i>) <i>paraindicus</i> McKee.....	X	X	X	X
<i>Waagenoconcha montpelierensis</i> (Girty).....	X	..	X	X
<i>Avonia dorsoconcava</i> McKee.....	X	..	....	...
<i>Avonia subhorrida newberryi</i> McKee.....	A	..	Aff.	Aff.
<i>Marginifera meridionalis</i> McKee.....	X	..	....	...
<i>Marginifera popei</i> (Shumard).....	X	?	X	X
<i>Pugnoides pinguis</i> (Girty).....	X	X	X	X
<i>Squamularia guadalupensis</i> (Shumard).....	A	X	A	X
<i>Spiriferina hilli</i> Girty.....	X	X	X	...
<i>Hustedia meekana</i> (Shumard).....	X	X	X	X
<i>Composita arizonica</i> McKee.....	A	..	..	..
<i>Composita subtilita</i> (Hall).....	X	X	X	..
<i>Dielasma phosphoriensis</i> C. Branson.....	X	..	....	..

X = present; A = abundant; Aff. = closely related.

identified from the normal marine facies (β , no. 1) of the Kaibab formation. Among these, it will be seen that of the 7 that are as yet unknown in the Texas section, 3 are represented there by affinities or closely similar forms. Counting the latter, the Kaibab fauna has 10 species in common with the Hess formation of Texas, 15 with the Leonard, and 12 with the Word.

²⁸ Robert E. King, *Geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, 1930.

Evidence given by the comparison of common species is not extremely convincing in demonstrating that the Kaibab is equivalent to the Leonard rather than to either the Word above or the Hess below. On the other hand, when it is noted that the most common Kaibab species are also abundant in the Leonard but not in the others, and, as pointed out by King, that *Productus bassi*—the most common species—does not occur above the Leonard, this correlation appears to be well justified.

Approaching the problem of Kaibab correlation from another viewpoint, it is apparent from evidence furnished by underlying formations that it must be fairly high in the Permian section. White²⁹ has shown on the basis of fossil floras that both the Hermit shale and the Supai formation of eastern Grand Canyon are of Permian age, and since these, as well as the Coconino sandstone and Toroweap formation, are below the Kaibab, it is obvious that in this area the latter is well above the base of the Permian. Further indirect evidence has been furnished by Longwell and Dunbar,³⁰ who found in southern Nevada beneath the Kaibab-Toroweap formations some 1200 feet of red Supai beds underlain by limestones of the Bird Spring formation, in part Permian. On the basis of fusulinids it was suggested that the upper 2950 feet of these were equivalent to the Wolfcamp-Leonard formations of the Texas section. If this correlation be correct, then the Kaibab cannot be older than the upper part of the Leonard.

In summation, the age of the Kaibab formation in terms of the Glass Mountain section in Texas is equivalent to that of the upper part of the Leonard because: (1) The Kaibab has more brachiopod species in common with the Leonard than with any other formation of the Glass Mountains. (2) Most of the brachiopods that are abundant in the Kaibab are also abundant in the Leonard. (3) The absence of *Productus bassi* in the Word formation and above in Texas practically precludes the possibility that the Kaibab, where this species is found in superabundance, is any younger than the Leonard. (4) The presence of a great thickness of Permian beds beneath the Kaibab suggests that it is well above the Permian base. (5) The tentative correlation, on the basis of fusulinids, of the uppermost Bird Spring limestone in the Nevada section with the lower Leonard of Texas suggests that the Kaibab is not older than upper Leonard.

The Leonard formation of Texas not only contains the normal brachiopods of the Permian such as are found in the Kaibab, but also certain of the aberrant Permian brachiopods, some cephalopods, and some fusulinids, all of which groups are absent from the Kaibab formation but are among the most important for stratigraphic work. Correlation of the Kaibab with other Permian deposits, especially those of the Old World, therefore can best be accomplished not by direct comparison of Kaibab species, but by inferring such relationships as have been established for the Leonard on the

²⁹ David White, *Some features of the early Permian flora of America*, Rept. XVIth Internat. Geol. Cong., Washington, pp. 7-8, 1933.

³⁰ C. R. Longwell and C. O. Dunbar, *Problems of Pennsylvanian-Permian boundary in southern Nevada*, Bull. Amer. Assoc. Petrol. Geol., vol. 20, no. 9, p. 1203, 1936.

basis of its extensive and varied fauna. For such correlations the reader is referred to the extensive literature on the Permian of west Texas.

COMPARISON WITH THE MANZANO GROUP

For many years there has been a general agreement among geologists that the Kaibab formation is a lateral equivalent of the uppermost part of the Manzano group of New Mexico, now known as the San Andres limestone (top of Chupadera formation).³¹ There seems to be no good reason to question the validity of this correlation, for it is based on the presence of a number of common species of invertebrates, some of them very diagnostic forms, in these two formations. King³² has compared the San Andres brachiopods with those of the Leonard formation of Texas—shown to be equivalent to the Kaibab—and indicated a great similarity in the assemblages.

Of the ten brachiopods described by Girty³³ from the San Andres, the following species are found also in the Kaibab: *Productus ivesi* (= *P. bassi*), *Productus occidentalis*, *Squamularia perplexa*? (= *S. guadalupensis*), *Composita subtilita*. In addition, *Marginifera cristobalensis* has been listed from the Kaibab (facies 5) of Circle Cliffs, Utah, by Girty.

As the correlation of the Kaibab with the San Andres limestone appears to be definite, the latter must be related to the seaway which connected the marine waters of the northern Arizona area with those of west Texas and the Coahuila, Mexico, region beyond,³⁴ during Middle Permian time. It should not be assumed from this, however, that the normal marine waters with their fauna as found in facies 1 of the Kaibab were present wherever the San Andres is present today. Lee and Girty³⁵ have shown by comparative sections that this top unit of the Manzano group thins northward and disappears in northern New Mexico and, more significant still, that the fauna contains a great preponderance of mollusks indicating "brackish water" conditions.

The nearest reported outcropping to the Kaibab of definite San Andres limestone is in the Zuni Mountains of west central New Mexico. This has been referred to as Kaibab by Darton³⁶ and undoubtedly is equivalent to it; however, an examination of its fauna readily shows that it was developed as a facies distinctly different from any of those that have been recognized in the Kaibab. A collection of brachiopods from Upper Nutria Pueblo,

³¹ For correlation tables see R. E. King, Univ. Texas Bull. 3042, pt. 2, p. 146, 1930; David White, Rept. XVIth Internat. Geol. Cong., p. 10, 1933; J. S. Williams, XVIth Internat. Geol. Cong., Guidebook 29, pl. 5, 1933.

³² R. E. King, *Geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, pp. 26-27, 1930.

³³ W. T. Lee and G. H. Girty, *The Manzano group of the Rio Grande Valley, New Mexico*, U. S. Geol. Surv. Bull. 389, 1909.

³⁴ R. E. King, *The Permian of southwestern Coahuila, Mexico*, Amer. Jour. Sci., 5th ser., vol. 27, p. 105, 1934.

³⁵ W. T. Lee and G. H. Girty, *The Manzano group of the Rio Grande Valley, New Mexico*, U. S. Geol. Surv. Bull. 389, p. 14, 1909.

³⁶ N. H. Darton, *Résumé of Arizona geology*, Univ. Ariz. Bull. 119, p. 96, 1925.

Zuni Reservation, sent the writer by Mr. Tom Meeks of the Soil Conservation Service showed that two of the four species reported as common at this locality are unknown from the Kaibab, thus suggesting the error of assuming a direct sea connection between these areas.

In brief, the main westward passageway from Texas for the cosmopolitan invertebrate faunas of the Middle Permian must have been across southern New Mexico and Arizona, with only lagoonal and other specialized environments to the north, and somewhere in central Arizona the shore line made a swing northward.

COMPARISON WITH THE SOUTHERN ARIZONA PERMIAN

The presence of strata of Middle Permian age in southern Arizona was first recorded by Darton, who stated in 1925 that "fossils of Kaibab age were found at several places in the southwestern counties."³⁷ A year later Stoyanow³⁸ described a section of Permian in the Chiricahua Mountains containing a light gray limestone, 500 feet thick, from which he collected *Productus ivesi* (= *P. bassi*), *P. occidentalis*, *Meekella pyramidalis*, *Derbya* sp., *Squamularia guadalupensis*, and *Aviculopecten coloradoensis*—all common forms of the Kaibab.

Further references to the Middle Permian of southern Arizona have been given by King;³⁹ he⁴⁰ has also discussed its occurrence in northwest Sonora to the south. The latest and most important contribution to our knowledge of these beds is by Stoyanow,⁴¹ who has proposed the name of Chiricahua limestone for the Kaibab equivalent.

Stoyanow has shown that the Chiricahua was probably developed in the main seaway of the Middle Permian, which connected with west Texas, and that northward the beds "grade into shallow-water and continental deposits." The connection of the marine waters of southern Arizona with the open-sea facies (β , no. 1) of the Kaibab must then have been in western Arizona. This concept is, of course, important to the palæogeographer and helps the stratigrapher explain certain faunal inconsistencies in the San Andres.

COMPARISON WITH THE PHOSPHORIA

As it is now generally agreed that the Phosphoria formation, or at least the upper portion of it, is of Permian age, and as its outcroppings are found throughout a vast area immediately north of that occupied by the Kaibab formation, it is very desirable from palæogeographic and other standpoints

³⁷ *Ibid.*, p. 71.

³⁸ A. A. Stoyanow, *Notes on recent stratigraphic work in Arizona*, Amer. Jour. Sci., 5th ser., vol. 12, pp. 318-319, 1926.

³⁹ R. E. King, *Geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, pp. 24-25, 1930.

⁴⁰ R. E. King, *The Permian of southwestern Coahuila, Mexico*, Amer. Jour. Sci., 5th ser., vol. 27, p. 98, 1934.

⁴¹ A. A. Stoyanow, *Correlation of Arizona Paleozoic formations*, Bull. Geol. Soc. Amer., vol. 47, pp. 532-533, 1936.

to know the relationship, if any, between these formations. The problem of correlation, however, is not a simple one.

As early as 1910 Girty pointed out that the fauna of the Phosphoria formation was highly specialized, "representing an extremely individual and novel facies."⁴² That this formation was developed in an unusual environment is suggested by the presence in it of extensive phosphate deposits and massive chert beds. This environment, therefore, very probably caused the peculiar differentiation of the faunas which is so apparent.

Because of its specialized character, the age of the Phosphoria fauna has been the subject of much difference of opinion. In 1927 Girty⁴³ gave a history of the viewpoints on its interpretation and reached the conclusion that because it appeared to correspond to an Alaskan fauna thought by Hottedahl to be Artinskian, the Phosphoria must also be Lower Permian. Other viewpoints, expressed since that time, have been summarized by Thomas,⁴⁴ but for convenience in further discussion will be repeated here.

E. B. Branson at first concluded that "the abundance of coeliodont sharks, which have never been reported from strata younger than the Pennsylvanian, indicates an age older than the Permian"⁴⁵ for the lower phosphate beds of the Phosphoria. More recently, however, he has revised his opinion, stating that "since other evidence shows that the Phosphoria is a single Permo-Carboniferous unit, the shark is believed to have a longer range than that previously established."⁴⁶

C. C. Branson⁴⁷ examined the Phosphoria of the Wind River Mountains, studied the fauna of the entire formation, and succeeded in differentiating the faunal zones. On the basis of this, he concluded that the lower Phosphate member was of late Pennsylvanian age, that the *Pustula* and *Hustedia* faunules above were Permo-Carboniferous with Pennsylvanian holdovers, and that the *Aulosteges* fauna near the top represented the lowermost part of the Permian. He believed that there was represented a gradation without break from Pennsylvanian to Permian.

King,⁴⁸ from his study of the Permian brachiopods of Texas, concluded that the age of the Phosphoria postulated by Branson was "unlikely" and that, on the basis of brachiopod comparison, this formation probably was to be correlated with the Word of Texas. He treated the formation as a single

⁴² G. H. Girty, *The fauna of the phosphate beds of the Park City formation in Idaho, Wyoming, and Utah*, U. S. Geol. Surv. Bull. 436, p. 8, 1910.

⁴³ G. H. Girty, in G. R. Mansfield, *Geography, geology and mineral resources of part of southeastern Idaho*, U. S. Geol. Surv. Prof. Paper 152, pp. 78-81, 1927.

⁴⁴ H. D. Thomas, *Phosphoria and Dinwoody tongues in lower Chugwater of central and southeastern Wyoming*, Bull. Amer. Assoc. Petrol. Geol., vol. 18, no. 12, 1934.

⁴⁵ E. B. Branson, *The lower Embarras of Wyoming and its fauna*, Jour. Geol., vol. 24, no. 7, pp. 639-665, 1916.

⁴⁶ E. B. Branson, *Carboniferous stratigraphy of Wyoming*, (abstract) Proc. Geol. Soc. Amer., p. 392, 1935.

⁴⁷ C. C. Branson, *Paleontology and stratigraphy of the Phosphoria formation*, Univ. Missouri Studies, vol. 5, no. 2, 1930.

⁴⁸ R. E. King, *Geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, pp. 30-33, 1930.

unit, however, not distinguishing the different members or faunules, nor indicating any considerable time difference between bottom and top zones as had Branson.

King recognized in the Phosphoria fauna a lower Permian aspect and states that "a large proportion of the Phosphoria species have close affinity to Russo-Arctic Lower Permian species." He explains this as the result of migration of Russian Lower Permian forms into the Alaska sea, where they remained with slight modification into Middle Permian times, while the Russian seaways were meanwhile cut off but marine connections were effected with the Phosphoria to the south.

The theory of Middle Permian age for the Phosphoria, as postulated by King, has been given support by the studies of Miller and Kline.⁴⁹ They conclude on the basis of cephalopods that the so-called "goniatite beds" of the phosphatic shale member are "most probably the correlative of part of the Word formation of west Texas but . . . may be as old as the Leonard." They recognize that this age applies only to the beds from which their fossils were obtained, and that, as suggested by Branson, the lower part of the formation may be considerably older. They suggest a Pennsylvanian age for it with a hiatus above.

Still another viewpoint on the age of the Phosphoria has been indicated by J. S. Williams,⁵⁰ who shows it on his correlation chart as equivalent to all of the Lower and Middle Permian but with upper and lower limits open to question. The uppermost portion is indicated as comparable in age with the Kaibab formation.

As has been indicated in the preceding discussion, the age of the Phosphoria has been interpreted in numerous ways with the result that this formation has been variously considered as older than the Kaibab, equal in part to the Kaibab, and younger than the Kaibab. In an effort to determine which of these correlations is correct, a careful search has been made, especially in the northernmost known exposures of the Kaibab, for evidence of the Phosphoria formation either above or below it. The results were negative.

If the deposits of southeastern Utah which are commonly referred to the Kaibab (facies 5 of this paper) are truly equivalent to the other beds of this formation, then the Kaibab is unquestionably to be correlated with the Phosphoria, at least in part, on the basis of fossils occurring in facies 5.⁵¹ On the other hand, if the Kaibab of the type locality is actually of different age from that of facies 5, the latter should be considered a southern extension of the Phosphoria and its deposits should be expected either above or below the type Kaibab somewhere to the south. Such apparently is not the case.

⁴⁹ A. K. Miller and L. M. Kline, *The cephalopods of the Phosphoria formation of northwestern United States*, Jour. Paleontol., vol. 8, no. 3, pp. 281-302, 1934.

⁵⁰ J. S. Williams, XVIth Internat. Geol. Cong., Guidebook 29, pl. 5, 1933.

⁵¹ See comparison between facies 1 and facies 5 of the Kaibab β member on page 168 for faunal relationships.

King⁵² suggests that Phosphoria deposits originally occurred above the type Kaibab and thus connected with the Word of Texas, but that they were entirely removed by erosion during the pre-Triassic interval. This explanation seems to the writer to be untenable because detailed studies of the Kaibab-Moenkopi unconformity have produced no evidence of such widespread stripping of overlying beds and because the α member limestone (referred to as *Bellerophon* limestone by King) apparently does not represent the base of a distinct stratigraphic unit which was characterized by a new fauna, but rather consists of deposits formed in relict waters of a retreating sea and contains a fauna of normal brackish-water types as found elsewhere in near-shore facies of the Kaibab.

Evidence based both on its brachiopod and on its cephalopod faunas points strongly toward a Middle Permian age for at least part of the Phosphoria, and of a sea connection across northern Arizona to west Texas, therefore the writer believes that the Kaibab formation must represent the deposits of this connecting sea. If this be true, then the marked change in fauna between the type Phosphoria, i. e. the *Pustula* member, and the type Kaibab (facies 1 of β member) is to be explained by the peculiar environmental factors known to have affected the former.

In support of the theory advanced in the preceding paragraph is the transition character of the Kaibab of southeastern Utah (facies 5). Although in the San Rafael Swell its fauna has a distinctly Phosphoria aspect, farther south in the Circle Cliffs it also contains some fossils of normal (facies 1) Kaibab type. In brief, this appears to be an area of mingling between northern and Texan species.

It seems probable, as already suggested by several geologists, that the Phosphoria represents a rather considerable period or perhaps several stratigraphic units. With the Kaibab this apparently is not the case. From a comparison with the faunal zones recognized by C. C. Branson, it is most likely to be the equivalent of the *Pustula* member. The latter not only contains *Pustula nevadensis*, *Waagenoconcha montpelierensis*, *Spirifer pseudocameratus*, a *Composita*, and a *Squamularia* found in facies 5 of the Kaibab, but also species of *Spiriferina*, *Pugnoides*, *Composita*, and *Hustedtia* which are not greatly different from species in facies 1 of the Kaibab. Since the latter has been shown almost certainly to be the equivalent of the uppermost Leonard of Texas, this correlation appears to be consistent with the facts.

⁵² R. E. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 32, 1930.

DESCRIPTION OF MEASURED SECTIONS

1. SECTION 4 MILES SOUTHEAST OF HOLBROOK, ARIZONA

Moenkopi formation:

Shale, red, brittle

Unconformity

Coconino sandstone:

Typical large-scale, cross-laminated sandstone

2. SECTION 11 MILES SOUTHEAST OF HOLBROOK, ARIZONA

Moenkopi formation:

Shale, red, brittle

Unconformity

Coconino sandstone:

Typical large-scale, cross-laminated sandstone

3. SECTION 22 MILES SOUTH OF HOLBROOK, 7 MILES NORTH OF SNOWFLAKE, ARIZONA

Moenkopi formation:

Shale, red, brittle

Unconformity

Kaibab formation:

Limestone, gray, thin-bedded; coated with travertine	Feet 1.0
--	-------------

Coconino sandstone:

Typical large-scale, cross-laminated sandstone

5. SECTION 4 MILES NORTHEAST OF PINEDALE, ARIZONA

Top of hill; recent erosion surface; pebbles on hill surface indicate Moenkopi not long removed

Kaibab formation:¹

α member:

- | | |
|---|------|
| 1. Limestone, dull gray, uniform-textured, thin-bedded, unfossiliferous; weathers to smooth, blocky surface; probably chemical precipitate .. | 2.0 |
| 2. Limestone, buff; beds 3 feet thick; weathers to gray, rough surface; very fossiliferous (<i>Euomphalus</i> and other mollusk molds) | 9.0 |
| 3. Sandstone, white at base, red-brown above, non-calcareous, very friable; uniform-sized grains weakly cemented; cross-laminated and gnarly-bedded | 16.5 |
| 4. Sandstone, brown and white; colors in irregular bands; beds 0.5-1 foot each; friable, non-calcareous; medium-sized grains among very fine | 11.0 |
| 5. Limestone, magnesian, light gray to dull gray, massive, fine-grained; weathers to prominent ledges; fossiliferous locally (molds of very small mollusks) | 15.5 |

¹ Section 1 mile farther south along road shows the following Kaibab:

Recent erosion surface	Feet
------------------------	------

- | | |
|---|------|
| 1. Sandstone, red-brown, cross-laminated on large scale (like Coconino), friable, uniform-textured; weathers to large flat, sloping slabs.....Exposed | 60.0 |
| 2. Limestone, medium to dark gray, dense, uniform-textured, thin-bedded..... | 6.0 |

6. Limestone, buff; weathers to ledges with gray, pitted surface; fossiliferous (molds of mollusks); gradation upward into sandstone, white, fine-grained, sugary, barren	Feet 24.0
Underlying beds concealed	

7. SECTION EAST END OF HEBER, ARIZONA

Top of hill; recent erosion surface

Kaibab formation:² α member (?):

1. Limestone, pale gray to cream, magnesian; weathers to pitted, dark gray-brown surface; fossiliferous (molds of mollusks common); resembles limestone in section 5	13.0
--	------

 β member (?):

1. Limestone, pale gray, hard, massive, fine-grained; beds 2-6 feet thick; uniform texture except near base where more sandy; fossiliferous at several horizons (at base <i>Bellerophon</i> , <i>Allorisma</i> , <i>Astartella</i> , <i>Schizodus</i> , <i>Plagioglypta</i>) Exposed	104.5
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11. SECTION AT CHEVELON CANYON NEAR JUNCTION WITH WEST CHEVELON,
ABOUT 25 MILES SOUTH OF WINSLOW, ARIZONA

Rim of canyon; recent erosion surface

Kaibab formation:

 α member:

1. Limestone, brown to lavender, gnarly, thick-bedded; locally sandy, locally magnesian	5.0
2. Limestone, brown, dense; weathers brown; locally fossiliferous (molds of mollusks)	20.0
3. Sandstone, white, sugary, calcareous	2.0
4. Limestone, gray to brown, magnesian, thin-bedded; weathers to slope with weak ledges, pitted surfaces; locally fossiliferous (molds of mollusks); much concealed	38.5
5. Limestone, gray to brown, very resistant; weathers to ledge with pitted surface; fossiliferous (<i>Productus bassi</i> , gastropod, pelecypod molds)	4.0
6. Limestone, mouse gray, thin-bedded, slightly sandy; weathers to smooth surface; forms shelf largely concealed	21.0

 β member:

1. Limestone, buff, sandy, massive; cap rock of canyon; full of quartz geodes	20.0
2. Sandstone, white to yellow, crumbly, calcareous, slope-forming	10.0
3. Limestone, gray, crystalline, grading upward into sandy limestone; beds average 1-2 feet thick; fossiliferous (<i>Productus bassi</i> , very common at 11 feet; pelecypods common at 27 feet); top unit of main cliff	33.0
4. Limestone, gray, crystalline, grading upward into sandy limestone; cycle like no. 3	9.0

² 12 miles north of Heber the limestone underlying the Moenkopi formation is buff to yellow, pitted, with molluscan fauna; typical α member.

5. Limestone, gray, crystalline, grading upward into sandy limestone; cycle like no. 3; fossiliferous (poorly preserved mollusk molds common)	Feet 29.0
6. Limestone, gray, crystalline, grading upward into sandy limestone; cycle like no. 3; fossiliferous (<i>Plagioglypta</i> , <i>Euphemus</i> , etc.)	32.5
7. Limestone, gray, crystalline, grading upward into sandy limestone; cycle like no. 3; fossiliferous (small, poorly preserved mollusk molds); beds massive, 5-20 feet	41.5
Unconformity: Slight erosion channels in Coconino filled with limestone Coconino sandstone:	
Typical large-scale cross-lamination	Exposed 50.0

12. SECTION ON EAST CLEAR CREEK, 3 MILES SOUTHEAST OF WINSLOW, ARIZONA
Moenkopi formation:

Sandstone, red, slightly cross-laminated, fairly hard, ledge-forming

Unconformity: Not apparent at this locality

Kaibab formation:

1. Limestone, brown, sandy, impure	2.0
2. Sandstone, white, sugary, flat-, thin-bedded; weathers brown with large pits; non-calcareous	8.0
3. Limestone, brown, impure; like no. 1 but less sandy; rough, pitted surface	2.0
4. Sandstone, white, sugary; resembles no. 2 but cross-laminated on small scale in a few beds; some large quartz grains scattered throughout; weathers with large pits, brown surface; contains iron concretions	14.0

Coconino sandstone:

Large-scale cross-laminations, salmon color, uniform texture; laminations truncated to flat upper surface

16. SECTION 10 MILES SOUTHWEST OF WINSLOW, ARIZONA

Moenkopi formation:

Shale, red

Unconformity: Contact line flat and without relief

Kaibab formation:

α member:

1. Limestone, tan to yellow, magnesian; weathers to pitted, rough gray surface locally stained pink; fossiliferous (molds of pelecypods, <i>Plagioglypta</i>)	Exposed 30.0
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17. SECTION AT MACK'S CROSSING OF EAST CLEAR CREEK, MOGOLLON PLATEAU, ARIZONA

Top of hill; recent erosion surface; basal conglomerate of Moenkopi not much above on adjoining hill

Kaibab formation:

α member (alternating sandstone and limestone):

1. Sandstone, yellow, non-calcareous, uniform-grained, thin-, flat-bedded; quartz grains fine, round, weakly cemented; weathers brown or red	Exposed 5.0
--	-------------

2. Limestone, dark gray, thin-bedded; weathers to rough pitted surface; partly concealed; fossiliferous (molds of mollusks)	Feet 42.0
3. Sandstone, white, calcareous, flat-, thick-bedded; contains lenses of pink, yellow, and white, thin, crumbly sandy shale near base; intraformational conglomerate near top	21.5
4. Limestone, dark gray; like no. 2; weathers to pitted surface; fossiliferous (molds of mollusks)	6.0
5. Sandstone, white to pink, calcareous, very fine-grained; bedding flat or gnarly	6.0
6. Limestone, dark gray, argillaceous; beds average 1 foot thick; weathers to pitted surface; fossiliferous (molds of pelecypods) ..	7.5
7. Sandstone, white, calcareous, very fine-grained; contains shale lenses and intraformational conglomerate	4.0
8. Limestone, gray; weathers to series of receding ledges with pitted surfaces; very fossiliferous (molds of mollusks)	8.0
9. Limestone, gray; weathers to ledge with smooth surface; fossils scarce	10.5
10. Sandstone, yellow, calcareous, fine-grained, flat-bedded	5.0
β member (?):	
1. Limestone, pale gray, massive; beds 10 feet thick; weathers to pitted surface; no fossils noted	21.5
2. Limestone; dull gray grading up into dark blue-gray; weathers into series of ledges, each 3 feet thick; fossiliferous at base (<i>Euphemus</i> , <i>Productus bassi</i> , pelecypod molds)	30.0
3. Limestone, gray, thin-bedded; weathers smooth, blocky	2.0
4. Limestone, dull gray; weathers to prominent black ledge; like no. 2 but thicker-bedded; very fossiliferous near top (<i>Productus bassi</i> , mollusk molds)	31.0
5. Limestone, buff, fine-grained, sandy, massive; alternating with thin-bedded, cherty limestone, as follows:	
a. Limestone, buff, thin-bedded; contains chert masses and concretions near base	13.4
b. Limestone, buff, sandy, massive; weathers dark gray; very fossiliferous (<i>Productus bassi</i> , <i>Archæocidaris</i> , erinoids)	12.5
c. Chert, dull white, bedded, hard but brittle	2.0
d. Limestone, buff, thin-bedded, sandy; contains irregular chert masses near base	25.5
e. Limestone, buff, massive; weathers to prominent black ledge; contains some irregular chert masses; fossiliferous (<i>Productus bassi</i> , <i>Archæocidaris</i> , erinoids)	13.0
f. Limestone, buff, thin-bedded, sandy; weathers to receding ledges	22.0
g. Limestone, buff, massive, sandy, ledge-forming; contains scattered chert nodules; very fossiliferous (erinoids, <i>Archæocidaris</i> , <i>Productus bassi</i>)	4.0
γ member:	
1. Limestone, gray to lavender, crystalline; massive below, thin-bedded (6 inches) above; unfossiliferous; green parting shales at top and base	9.5

2. Limestone, dull gray, argillaceous, massive; beds 5-10 feet thick; weathers to dark gray cliff with pitted surface; fossiliferous (<i>Myalina</i> , <i>Schizodus</i> , <i>Allorisma</i> , <i>Euphemus</i> , etc.)	Feet 22.0
Unconformity: Erosion surface shown by variable thickness of underlying bed	

Coconino sandstone:

1. Sandstone, white, calcareous, flat-bedded; composed of fine quartz elastics scattered through limy matrix 6.5-16.0
2. Sandstone, white, non-calcareous, highly cross-laminated; laminations beveled to flat upper surface Exposed 200.0 $\pm$

18. SECTION AT JUNCTION OF EAST CLEAR CREEK AND MILLER CANYON, ARIZONA

Summit of hill; recent erosion surface

Kaibab formation:

 α member:

1. Limestone, gray, sandy; forms ledge; fossiliferous (*Productus bassi*, *Bellerophon*, *Allorisma*, *Plagioglypta*, *Marginifera*); see no. 1 in section 21 Trace
2. Sandstone, yellow, fine-grained, calcareous, prominently cross-bedded (æolian?) 12.0
3. Limestone, gray, magnesian, fine-grained; fossiliferous (molds of *Schizodus* and gastropods) 18.0
4. Limestone, lavender, sandy, dolomitic 1.0
5. Sandstone, lavender, non-calcareous, fine-grained, thin-bedded 4.0
6. Limestone, mouse gray; free of elastics; fossiliferous (abundant molds of gastropods and pelecypods) 16.5

 β member:

1. Chert, yellow, red, and white, hard, bedded 2.0
2. Limestone, gray, hard, crystalline; contains many geodes and quartz aggregates 13.5
3. Chert, yellow, red, and white; like no. 1 2.5
4. Limestone, gray, crystalline; fossiliferous near base (*Archæocidaris*, *Productus bassi*, bryozoa); contains many geodes and quartz aggregates 32.0
5. Chert, yellow, red, and white; like no. 1 4.0
6. Limestone, buff, sandy, dolomitic; fossiliferous in upper part (*Productus bassi*, *Archæocidaris*, bryozoa, crinoids); contains nodules above base 33.0
7. Sandstone, red, crumbly, non-calcareous; forms slope; fossiliferous (bryozoa) 3.5
8. Limestone, buff, sandy, dolomitic; like no. 6 and containing same fossils; nodules occur above 4 feet, abundant at top, which is barren of fossils 16.0

 γ member:

1. Limestone, buff; weathers to prominent gray and black ledge; very fossiliferous (molds of gastropods and large pelecypods) 26.5
2. Sandstone, yellow and red, crumbly; quartz grains of two sizes; largely concealed 14.5

Coconino sandstone: Feet
 Typical large-scale cross-laminations beveled to flat upper surface;
 about 50 feet exposed

19. SECTION ON MOGOLLON RIM, 8 MILES WEST OF COCONINO-SITGREAVES
 BOUNDARY, ARIZONA

Top of hill; erosion surface

Kaibab formation:

β member:

1. Sandstone, yellow, friable, flat-bedded; fossiliferous (*Productus bassi* common)

2. Chert, white, locally highly colored, bedded, hard but brittle

Concealed; probably covers sandstone like no. 1 38.0

Coconino sandstone:

Sandstone, white, sugary, cross-bedded on large scale; forms massive cliff 300.0 $\pm$

20. SECTION ON MOGOLLON RIM ABOVE WASHINGTON PARK, SOUTHEAST OF
 LONG VALLEY, ARIZONA

Concealed area on hillside; talus

Kaibab formation:

β member:

1. Limestone, gray, massive, sandy, ledge-forming; contains bands of nodular and large spherical concretions; very fossiliferous (bryozoa, two types, *Archæocidaris*, *Productus bassi*, *Composita*, *Spiriferina*)

Exposed 4.0

2. Chert, white, brittle, bedded 2.0

Concealed; talus-covered slope 58.0

Coconino sandstone:

Sandstone, white, sugary, cross-bedded on large scale; forms massive cliff

21. SECTION AT LONG VALLEY ON MOGOLLON PLATEAU, ARIZONA

Surface of recent erosion

Kaibab formation:³

α member:

1. Limestone, blue-gray, ledge-forming; free of elastics; fossiliferous (*Productus bassi*, *Bellerophon*, *Allorisma*, *Marginifera*)

2. Limestone, gray, sandy, ledge-forming

3. Sandstone, yellow, calcareous, fine-grained, cross-laminated; resembles Coconino 12.0

4. Limestone, gray, magnesian, fine-grained; fossiliferous (molds of *Schizodus* and gastropods)

22. SECTION AT CLOVER CREEK, 0.5 MILE WEST OF MAIN ROAD,
 MOGOLLON PLATEAU, ARIZONA

Eroded hilltop; covered with residual chert and some limestone in which was found *Productus occidentalis*

³ Compare with section 18 for more complete data.

Kaibab formation:

β member:	Feet
1. Limestone, light gray, crystalline; weathers gray; very fossiliferous (<i>Chonetes subliratus</i> , <i>Derbya</i> , <i>Meekella</i> , <i>Squamularia</i>)	6.5
Concealed	30.0
2. Limestone, light brown, crystalline, ledge-forming; weathers nearly black; fossiliferous (<i>Productus bassi</i> , crinoids, <i>Archæocidaris</i> , bryozoa, two types, <i>Chonetes</i>)	3.0
γ member:	
1. Limestone, buff to pink, massive, impure; weathers to light gray ledge; fossiliferous (abundant mollusk molds)	2.5
Concealed	9.0
2. Limestone, buff; like no. 1; very fossiliferous	8.0
Concealed	15.5
3. Limestone, buff; like no. 1; very fossiliferous	7.5

Unconformity: Relief of 14 feet recorded in width of canyon (200 yards)

Coconino sandstone:

Typical large-scale cross-lamination eroded to undulating top surface

23. SECTION IN PIVOT CANYON, 0.5 MILE WEST OF MAIN ROAD,
MOGOLLON PLATEAU, ARIZONA

Eroded hilltop; concealed surface

Kaibab formation:

β member: ⁴	
1. Limestone, gray, crystalline; fossiliferous (<i>Productus bassi</i> , crinoids, <i>Archæocidaris</i>)	
2. Limestone, light brown, crystalline, ledge-forming; fossiliferous (<i>Productus bassi</i> , <i>Chonetes</i> , crinoids)	10.0
γ member:	
1. Limestone, buff, massive, impure; fossiliferous (molds of mollusks abundant)	42.0

Unconformity: Surface of relief indicated by changes in thickness of γ member up canyon

Coconino sandstone:

Typical large-scale cross-laminations

24. SECTION AT SCHNEBLEY HILL, MOGOLLON PLATEAU, ARIZONA

Basalt

Kaibab formation:

α member:	
1. Limestone, red (coloring probably due to overlying lava), impure, thin-bedded; weathers to rough ledges	12.0
Concealed	19.0
2. Limestone, gray, magnesian, ledge-forming; beds alternate between pitted, fossiliferous type (molds of mollusks) and smooth-surfaced, barren type	27.0

⁴ A much higher horizon of β member is represented along the road at the divide between Clover Creek and Pivot Canyon. Limestone, white to cream, soft, claylike; weathers in large blocks with cream surface; very fossiliferous (*Composita arizonica*, *Productus bassi*, *Productus occidentalis*, *Aviculopecten*, bryozoa of three types, *Spiriferina hilli*).

	Feet
Concealed	28.0
3. Limestone, gray, magnesian, ledge-forming; composed of two types like no. 2; fossiliferous (molds of mollusks)	55.0
4. Limestone, yellow, crumbly	3.0
5. Limestone, blue-gray, magnesian; lower part weathers to pitted surface, upper part smooth; very fossiliferous (<i>Euomphalus</i> , <i>Plagioglypta</i> , and others)	30.0
6. Limestone, yellow, fine-grained; barren; contains a few concretions	18.0
7. Limestone, gray, magnesian, ledge-forming; weathers to pitted surface; very fossiliferous (molds of mollusks)	4.0
β member:	
1. Limestone, cream to buff, sandy, fine-grained; weathers to massive ledges with rounded surfaces; contains chert beds at base, 4 feet above, 28 feet above; geodes and concretions local	83.0
2. Limestone, buff, sandy, fine-grained; weathers to series of ledges with smooth surfaces	18.0
3. Chert, dull white, bedded, hard but brittle	5.0
4. Limestone, reddish brown; weathers to buff, massive ledge with pitted surface; contains nodules; fossiliferous (<i>Productus bassi</i> , <i>Archæocidaris</i>)	6.0
5. Dolomite, buff, sandy, slabby, fine-grained; full of irregular patches of dull white chert	8.0
6. Limestone, buff to pink, sandy, fine-grained; weathers to series of ledges (2-4 feet thick) with smooth surfaces; contains geodes locally	34.0
7. Chert, white, bedded, hard but brittle	2.0
8. Limestone, gray and red, fine-grained; contains irregular hard, white nodules; fossiliferous (indeterminable molds)	6.0
9. Limestone, yellow, very sandy; weathers to ledge with gray and pink surface; contains many geodes	4.0
10. Limestone, buff to yellow; fine elastic grains throughout; weathers to massive, pitted cliff	14.0
11. Sandstone, white, calcareous, flat-bedded; weathers to rounded surface	5.0
Toroweap formation, eastern phase:	
Sandstone, white, cliff-forming; cross-laminations of several types, mostly within flat-lying beds; not measured	
Coconino sandstone:	
Typical large-scale cross-laminations; forms great cliff	

25. SECTION ON WEST SIDE OF OAK CREEK CANYON, NEAR HEAD

Rim of canyon; recent erosion surface

Kaibab formation:

 α member:

- | | |
|---|------|
| 1. Limestone, white to buff, sandy; weathers gray; very fossiliferous (molds of small mollusks) | 12.0 |
|---|------|

 β member:

- | | |
|---|------|
| 1. Chert, yellow and white, hard, brittle, bedded | 2.0 |
| 2. Sandstone, light brown, calcareous, fine-grained; weathers to ledge with gray surface; contains geodes | 16.5 |

	Feet
3. Chert, yellow and white, hard, brittle; like no. 1	1.0
4. Limestone, yellow, sandy; weathers to receding brown ledges with talus between; fossiliferous at base (<i>Productus bassi</i>)	78.0
5. Chert, dull white, brittle; largely concealed; ledge	8.0
6. Limestone, buff, very sandy; weathers to rough gray surface; fossiliferous at top (<i>Productus bassi</i>)	12.0
7. Limestone, gray; like no. 6 but only slightly sandy; weathers to series of gray, rough ledges (3-4 feet thick); top half contains salmon-colored quartz aggregates	61.0
8. Sandstone, white, calcareous, fine-grained, flat-bedded; forms ledge	5.0
9. Sandstone, brown, crumbly, very calcareous, thin-bedded	1.0-2.0
Unconformity: Slight relief of surface exhibited; erosion pockets filled with overlying brown sandstone	
Toroweap formation, eastern phase:	
1. Sandstone, white to yellow, medium-grained, non-calcareous; series of flat beds each contains similar cross-lamination; cliff-forming ...	247.5
2. Sandstone, white to yellow; like no. 1 but slope-forming	82.5
Coconino sandstone:	
Typical large-scale cross-laminated sandstone	

26. SECTION IN PADRE CANYON AT HIGHWAY 66

Rim of canyon; recent erosion surface; Moenkopi probably was not much above, since found on mesas near by

Kaibab formation:

α member:

- | | |
|--|------|
| 1. Limestone, tan; beds 0.5-1 foot thick; weathers to light gray, pitted surface; fossiliferous (molds of mollusks common) | 50.0 |
|--|------|

β member (?):

- | | |
|---|--------------|
| 1. Limestone, white to light gray, massive; beds 4-6 feet thick; fossiliferous (molds of mollusks common) | Exposed 50.0 |
|---|--------------|

Underlying beds concealed

27. SECTION ON EAST SIDE OF WALNUT CANYON, ARIZONA

Rim of canyon; recent erosion surface

Kaibab formation:

α member:

- | | |
|--|------|
| 1. Limestone, gray, magnesian; weathers to series of receding ledges with rough, pitted surfaces; very fossiliferous near base (pelecypod and gastropod molds) | 55.0 |
| 2. Limestone, creamy gray, soft; free of clastics; weathers with appearance of breccia | 4.0 |
| 3. Sandstone, white, fine-grained, calcareous | 6.0 |
| 4. Dolomite, light gray; weathers to pitted surface; fossiliferous (molds of mollusks) | 16.5 |
| 5. Limestone, light gray, slightly sandy, thin-bedded; weathers to pitted surface; fossiliferous (pelecypod molds) | 6.0 |
| 6. Limestone, light gray, thin-bedded; weathers to pitted surface; fossiliferous (molds of small mollusks) | 26.0 |

β member (?) :	Feet
1. Sandstone, white, calcareous, fine-grained; basal 30 feet forms cliff, receding ledges (4-5 feet thick above); contains salmon-colored geodes; contains thin bed of white chert 5 feet above base	46.0
2. Chert, white; weathers to recess	5.0
3. Limestone, white, sandy, and Sandstone, white, calcareous, fine-grained; salmon-colored geodes locally common, weathers to cliff of rough, gray surface	31.0
4. Dolomite, cream, impure, ledge-forming, soft; fossiliferous (<i>Archæocidaris</i>)	11.0
5. Dolomite, yellow, impure, cliff-forming; like no. 4 but harder, more yellow; weathers gray	25.5
6. Sandstone, white, calcareous, fine-grained, soft; fossiliferous (crinoids, <i>Archæocidaris</i> , <i>Productus bassi</i>); weathers to recess containing cliff dwellings	10.0
7. Limestone, buff, sandy, resistant; weathers to series of ledges (each 2-10 feet thick) with dark gray, rough surface; fossiliferous (molds of pelecypods, <i>Pleurotomaria</i> ; near top a sponge, <i>Productus bassi</i> , bryozoa)	50.0
γ member:	
1. Limestone, yellow and gray-brown, impure; weathers to series of ledges, each about 2 feet; fossiliferous at base and at top (molds of pelecypods)	11.0
2. Sandstone, yellow-brown, calcareous, weakly cemented, medium-grained; weathers to rough, dark surface	2.0
Toroweap formation, eastern phase (?) :	
White, cross-laminated sandstone with flat upper surface; mostly in beds but resembling Coconino in many places	

28. SECTION ON WEST SIDE OF SYCAMORE CANYON, ARIZONA

Moenkopi formation:

1. Shale, red
2. Conglomerate, limestone, gray, fills channels in Kaibab formation

Unconformity: Shallow channels of erosion present

Kaibab formation:

 α member:

1. Limestone, light gray, magnesian; weathers to pitted surface; fossiliferous (molds of *Bellerophon* and other mollusks)

66.0

 β member:

1. Limestone, white, sandy; locally contains lenses of coarse, rounded quartz grains
2. Limestone, light gray to buff; fossiliferous (abundant *Schizodus* molds)
3. Limestone, buff, slightly sandy; contains many quartz geodes and rows of brown elliptical concretions
4. Chert, white, irregularly bedded; weathers to recess
5. Limestone, gray, sandy; elastic quartz grains scattered throughout
6. Chert, white; like no. 4

6.5

4.5

33.0

2.0

7.0

4.0

7. Sandstone, white, massive, fine-grained with larger grains throughout, calcareous; large spherical lime concretions containing fossils (<i>Chonetes kaibabensis</i> , crinoids)	Feet 27.5
8. Chert, white, dull; contains tongues of yellow sandstone; weathers to recess in cliff which is composed of nos. 8-13	21.0
9. Limestone, gray, sandy, fine-grained; weathers to massive ledges 5-10 feet thick; contains spherical, brown concretions in middle ..	22.0
10. Chert, white, dull; like no. 8	28.5
11. Limestone, gray, sandy; like no. 9	2.0
12. Chert, white, dull; like no. 8	13.0
13. Limestone, gray, sandy; like no. 9; base of cliff (nos. 8-13); contains concretions with fossils (<i>Productus bassi</i>) near base	16.0
14. Sandstone, buff, grading upward into Limestone, gray, fossiliferous (<i>Archæocidaris</i> , <i>Productus bassi</i> , crinoids); massive beds 4-8 feet thick; recess at top; base concealed .	106.5
Toroweap formation, transition phase:	
1. Sandstone, white, calcareous, cross-laminated; quartz grains of two sizes (very fine and medium); forms ledge	9.5
2. Sandstone, red, fine-grained, crumbly, irregularly bedded; forms slope	49.5
3. Sandstone, white, cross-laminated; like no. 1	5.0
4. Sandstone, yellow and red, crumbly, irregularly bedded; forms slope	6.0
5. Sandstone, white, cross-laminated; like no. 1	2.0
6. Sandstone, red, crumbly; like no. 2	3.0
7. Sandstone, white, cross-laminated, uniform-grained, quartzitic	1.5
8. Sandstone, red, calcareous; quartz grains as in no. 7; resistant, ledge-forming	6.0
9. Sandstone, white, cross-laminated; like no. 1	20.0
10. Sandstone, red, crumbly; like no. 2	18.5
11. Sandstone, white, cross-laminated; like no. 1	3.0
12. Sandstone, red and yellow, crumbly; like no. 2	8.5
13. Sandstone, white, cross-laminated; like no. 1	3.0
14. Sandstone, yellow, flat-bedded, fine-grained; upper 2 feet gnarly, brecciated, interbedded with white sandstone like that above	20.0

Coconino sandstone:

Typical large-scale cross-laminations, truncated to flat upper surface

30. SECTION IN AUBREY CLIFFS, NORTHWEST OF SELIGMAN, ARIZONA

Top of hill; recent erosion surface

Kaibab formation:

β member:

- | | | |
|--|---------|-----|
| 1. Limestone, gray, pure, crystalline; fossiliferous (<i>Meekella</i> , <i>Productus bassi</i> , sponge, <i>Avonia</i>) | Exposed | 5.0 |
| 2. Limestone, gray, pure; grades upward into cherty beds and, near top, to bedded chert with tongues of yellow sandstone; weathers into receding ledges at bottom but massive cliff above; very fossiliferous except in chert beds (<i>Productus bassi</i> , <i>Squamularia</i> , crinoids, <i>Productus occidentalis</i> , bryozoa, <i>Composita arizonica</i> , <i>Avonia subhor-</i> | | |

<i>rida newberryi</i> , colonial coral, <i>Derbya</i> , <i>Waagenoconcha</i> , <i>Aviculopecten</i> , <i>Spiriferina</i> , <i>Chonetes subbliratus</i>)	Feet 28.0
3. Limestone, gray, sandy, cliff-forming; contains brown quartzitic concretions and bands; fossils scarce (<i>Productus bassi</i>)	47.0
4. Limestone, gray; contains many small, brown, irregular or branching concretions	3.0
5. Limestone, light gray, crystalline; weathers to rounded ledges; contains a few large, spherical, brown concretions; fossiliferous (<i>Chonetes kaibabensis</i> , erinoids)	22.0
Concealed	8.0
6. Limestone, gray-brown, crystalline; contains many white chert nodules	5.0
7. Limestone, gray-brown, crumbly; resembles overlying but without chert; weathers to rounded blocks; fossiliferous (erinoids abundant); fills erosion channels in sandstone	2.0-5.0
Unconformity: Shallow channels of erosion present	
Toroweap formation:	
α member:	
1. Sandstone, yellow, crumbly	8.5
2. Limestone, gray, impure, magnesian; much brecciated except in top 6 inches, where <i>Schizodus</i> sp. is abundant	4.0
3. Sandstone, red and yellow, crumbly; weathers to slope; largely concealed	55.0
4. Conglomerate, intraformational; consists of angular fragments of gray limestone and red sandstone in matrix of yellow sandstone; forms ledge	1.0
5. Sandstone, red and yellow, crumbly; like no. 3	38.0
β member:	
1. Limestone, dark gray, magnesian, very thin-bedded; weathers to smooth surface	6.0
2. Limestone, pale gray, crystalline; free of elastics; weathers to brown pitted surface; contains abundant large, dark brown chert nodules in irregular bands for 6 feet beginning 22 feet above base; beds average 2-4 feet thick; fossiliferous, especially near base (erinoids, <i>Productus ivesi</i> , <i>Meekella</i>)	44.0
3. Limestone, yellow-gray, thin-bedded, sandy, magnesian, hard; weathers to smooth face, sharp edges, and brown color	13.0
4. Limestone, lavender, crystalline, massive; beds thick (2-3 feet); weathers to series of ledges with gray, pitted surface; contains many geodes; fossiliferous (<i>Productus ivesi</i> , <i>Archæocidarid</i>)	91.0
5. Limestone, gray, sandy; weathers gray; contains many geodes; fossiliferous (<i>Productus ivesi</i>)	14.0
6. Limestone, lavender, crystalline; weathers to gray, pitted cliff; like no. 4 lithologically; fossiliferous (molds of pelecypods and <i>Bellerophon</i> ?)	17.0
7. Limestone, banded yellow and lavender, sandy, magnesian, crumbly; weathers to slope	2.5
8. Limestone, brown, hard; beds average 6 inches; fossiliferous, outlines indeterminable	3.0

	Feet
γ member:	
1. Sandstone, red, fine-grained, hard, calcareous; weathers to ledge with rough, dark-brown surface; beds 0.5–4 feet thick, thinnest at top ..	11.0
2. Sandstone, red, calcareous, fine-grained, soft, crumbly; weathers to slope	11.0
Coconino sandstone:	
Typical highly cross-laminated sandstone beveled to nearly flat (slightly undulating) surface	

31. SECTION AT TOLCHICO ON LITTLE COLORADO

Moenkopi formation:	
1. Shale, red	
2. Conglomerate; pebbles of Kaibab in red silt matrix	3.0
Unconformity: No relief exhibited where examined	
Kaibab formation:	
α member:	
1. Sandstone, yellow, calcareous, sugary; beds 2–3 feet thick; includes a bed of hard, yellow limestone; weathers to pitted surface	14.0
β member (?):	
1. Limestone, brown, very sandy, massive; beds each 15–20 feet thick; cliff-forming; very fossiliferous (molds of pelecypods and gastropods)	Exposed 60.0

32. SECTION AT GRAND FALLS OF THE LITTLE COLORADO

Moenkopi formation:	
1. Shale, red	
2. Conglomerate, composed of fine pebbles of chert and limestone, mostly angular, in red sandy matrix	2.0
Unconformity	
Kaibab formation:	
α member:	
1. Limestone, yellow-brown, magnesian; weathers to rough pitted surface; forms 2–3-foot ledges; lower part grades downward into white, sandy limestone	33.0
β member:	
1. Dolomite, gray, hard, contains beds of calcareous sandstone; weathers to rounded ledges and forms main cliff; very fossiliferous (pelecypods, gastropods, <i>Productus bassi</i>)	88.0
2. Limestone, yellow, sandy; similar to overlying but more sandy and separated from it by sandy ledge; weathers to brown, rough surface; very fossiliferous in some horizons (<i>Plagioglypta</i> , <i>Bellerophon</i> , etc.)	46.0
3. Sandstone, red, fine-grained; weathers to massive ledge; grades into overlying limestone; fossiliferous with poorly preserved molds	20.0
4. Sandstone, white, non-calcareous, sugary, flat- and irregularly bedded; weathers to recess under cliff (may represent Toroweap formation)	4.0

33. SECTION AT CITADEL SINK

Lava flow; basalt	
Moenkopi formation:	Feet
Shale, red, thin-bedded	12.0
Unconformity: Not apparent; surface flat	
Kaibab formation:	
α member:	
1. Limestone, reddish brown, magnesian, thin-bedded (0.5-2 feet); weathers to gray, pitted surface; very fossiliferous throughout, especially near top (pelecypod and gastropod molds); some crumbly, flat-bedded, white sandstones among limestone beds	50.0
2. Sandstone, white, crumbly	1.5
β member (?):	
1. Limestone, buff, sandy; weathers red or black, in cliff with straight face; beds 1-4 feet thick; fossiliferous (pelecypods); full of geodes	27.5
2. Chert, dull white; interfingers with crumbly sandstone; weathers into recess	1.0
3. Limestone, buff, sandy; like no. 1	6.5
4. Chert, dull white; like no. 2	1.0
5. Limestone, buff, sandy; like no. 1	13.0
Concealed; bottom of sink	

35. SECTION ON GRANDVIEW-FLAGSTAFF ROAD, 30 MILES SOUTH OF
GRAND CANYON ⁵

Summit of hill; recent erosion surface	
Kaibab formation:	
α member:	
1. Limestone, gray, thin-bedded, magnesian; weathers to series of ledges with pitted surfaces, some yellow; fossiliferous at 60 feet above base (molds of <i>Plagioglypta</i> , pelecypods)	Exposed 143.0
Base not exposed	

36. SECTION ALONG LITTLE COLORADO ABOUT 10 MILES WEST OF
CAMERON, ARIZONA

Top of canyon; recent erosion surface	
Kaibab formation:	
β member:	
1. Chert, red and yellow, hard, bedded	3.0
2. Limestone, gray, magnesian; free of elastics; weathers to brown, rough ledge	11.0
3. Chert, red and yellow, hard, bedded	3.0
4. Limestone, gray, magnesian and buff, sandy; beds 1-2 feet thick; weathers to series of receding ledges with pitted, light brown to pale gray surface; contains some geodes; fossiliferous (molds of pelecypods)	35.0
5. Sandstone, yellow, friable, thin-bedded	3.0

⁵ This section shows the greatest thickness known of α -member limestones without red beds or gypsum.

6. Limestone, gray to buff, fine-grained, hard, uniform-textured; beds 2-4 feet thick; weathers to massive ledges in sheer cliff, dark gray to red-brown; elastic sand largely absent; contains some geodes; chert present in soft zones or recesses (nodular concretions at 71 feet, 105 feet, 149 feet; earthy bedded chert at 198 feet); fossiliferous (molds of <i>Bellerophon</i> , <i>Astartella</i> , etc. at 165 feet; abundant molds of <i>Plagioglypta</i> and pelecypods at 214 feet)	214.5
Toroweap formation, eastern phase:	
1. Sandstone, white, calcareous, massive; bedding gnarly, locally cross-laminated on large scale; weathers to rounded ledge or to cliff	35.0
Coconino sandstone:	
Typical large-scale cross-laminations beveled to flat upper surface; 600 + feet exposed	

37. SECTION ALONG LITTLE COLORADO, BASE OF WATERLOO HILL

Recent erosion surface

Moenkopi formation:

- | | |
|--|-------|
| 1. Conglomerate and sandstone, yellow, impure, irregular bedding | |
| 2. Shale, bright red, crumbly, locally sandy | 11.0 |
| 3. Sandstone, light gray, fine-grained, sugary | 0-2.0 |

Unconformity: Angular discordance of a few degrees which cuts out bed 3 to west

Kaibab formation:

 α member:

- | | |
|---|------|
| 1. Limestone, yellow-brown, magnesian; weathers to ledge with rough, pitted surface; very fossiliferous (molds of gastropods and pelecypods) | 16.0 |
| 2. Sandstone, white, sugary, cross-laminated | 2.0 |
| 3. Sandstone, red, crumbly, fine-grained, irregularly bedded | 2.0 |
| Concealed; probably like no. 3 | 13.5 |
| 4. Limestone, gray, magnesian; weathers to two ledges with pitted surfaces; fossiliferous (molds of gastropods and pelecypods) | 11.0 |
| Concealed | 11.0 |
| 5. Sandstone, white, fine-grained with coarser grains scattered throughout; contains lenses of bright yellow chert and limonite structures .. | 12.0 |
| 6. Limestone, light gray; free of elastics; weathers to smooth rounded surface | 2.0 |
| 7. Limestone, dark gray and brown; like no. 1; fossiliferous (pelecypod molds) | 9.0 |
| 8. Sandstone, white, fine-grained, strongly cross-laminated; laminations steep, straight, short; top of bed flat; weathers to ledge with straight face and gray, pitted surface | 6.0 |

 β member:

- | | |
|--|------|
| 1. Sandstone, yellow, crumbly; beds thin (1-2 feet) and irregular, separated by layers of secondary quartz (2-12 inches thick) | 10.0 |
| 2. Sandstone, yellow, resistant, ledge-forming | 50.0 |
| 3. Chert, dull white, hard but brittle; contains tongues and lenses of yellow sandstone; weathers to recess | 2.0 |
| 4. Limestone, yellow, sandy; filled with geodes | 2.0 |

	Feet
5. Limestone, light gray, sandy; weathers to small blocks	1.0
6. Sandstone, white, calcareous; weathers to ledges with brown, irregular surface; locally full of geodes	16.0
7. Chert, white, hard but brittle; like no. 3	1.0
8. Limestone, gray, dolomitic; layers alternating with Sandstone, yellow, fine-grained, friable; weathers to recesses. Total forms sheer, massive cliff with general gray color, often pitted; dolomites full of geodes; fossiliferous at 115 feet from base (<i>Bellerophon</i> and others)	146.0
9. Chert, white, hard but brittle; like no. 3	5.0
10. Limestone, gray, hard, sandy; locally almost a sandstone; forms ledges 1-4 feet thick	23.0
11. Dolomite, light gray, sandy; small irregularly shaped concretions extremely abundant; weathers to slope	7.5
12. Dolomite, gray, hard, sandy; weathers to ledges; secondary quartz abundant near top	15.0
13. Sandstone, gray, crumbly; forms recess	2.0
14. Dolomite, gray, hard; free of clastics; contains geodes; weathers to ledge	5.0
15. Sandstone, light gray; forms ledges 2-4 feet thick; contains geodes	16.5
16. Limestone, light gray, dolomitic; weathers to ledge with pitted surface; contains many geodes; fossiliferous (<i>Bellerophon</i> , <i>Plagioglypta</i> , <i>Schizodus</i>) at top	5.0
Unconformity: Warping (?) and beveling of underlying beds; removal of 36 feet in 0.25 mile	
Toroweap formation, eastern phase:	
1. Sandstone, yellow, cross-laminated; laminations short, steeply inclined; beds or layers 5-10 feet thick; weathers black	6.0-40.0
2. Sandstone, red, yellow, and white; irregular bedding; forms slope; probably equals γ member to west	8.5
Coconino sandstone:	
Typical highly cross-laminated sandstone beveled to flat upper surface, apparently slightly undulating at this locality	
38. SECTION IN LEE CANYON AT WATERLOO HILL, ARIZONA	
Moenkopi formation:	
1. Shale, red	
2. Conglomerate	
Unconformity	
Kaibab formation:	
α member:	
1. Limestone, gray, ledge-forming; weathers to pitted surface	4.0
2. Sandstone, red, crumbly; gnarly bedding; weathers to slope	16.5
3. Limestone, gray, magnesian; weathers to pitted surface; contains lenses of thin shale	16.5
4. Chert, yellow and red, hard, brittle, bedded	7.0
5. Limestone, gray, magnesian, ledge-forming; weathers to pitted surface	11.0
6. Sandstone, white, flat-bedded, sugary; weathers to series of receding ledges	14.0

- | | |
|---|-------------|
| 7. Sandstone, buff, prominently cross-laminated, ledge-forming, calcareous; medium-sized quartz grains scattered through fine silt and lime; weathers brown and pitted | Feet
5.0 |
| 8. Limestone, dull gray, magnesian; contains scattered quartz grains; cross-laminated layer 10 feet above base; fossiliferous (molds of mollusks) | 33.0 |
| 9. Sandstone, white, weathers to smooth face; grades upward into limestone of no. 8 | 11.0 |
| 10. Sandstone, light gray, calcareous, much cross-laminated (with short, curving laminations); medium-sized quartz grains scattered through fine silt and lime; weathers to massive cliff | 13.0 |

 β member:

- | | |
|---|-------|
| 1. Limestone, gray, fine-grained, sandy, alternating with Sandstone, buff, fine-grained, calcareous; beds near base 2 feet thick, above 4-6 feet thick; weathers to series of receding ledges and recesses; contains hard, white, nodular concretions scattered through lower one-third, geodes above | 159.5 |
| 2. Limestone, gray, sandy, fine-grained, massive, alternating with Sandstone, yellow, crumbly and chert, gray, nodular | 146.0 |
| a. Sandstone, recess | 3.0 |
| b. Limestone, ledge | 13.0 |
| c. Sandstone and chert, recess | 4.0 |
| d. Limestone, ledge | 16.5 |
| e. Sandstone, recess | 2.0 |
| f. Limestone, ledge | 18.0 |
| g. Sandstone and chert ... | 4.0 |
| h. Limestone, ledge | 12.0 |
| i. Sandstone and chert .. | 2.0 |
| j. Limestone, ledge | 14.5 |
| k. Chert concretion bed .. | 2.0 |
| l. Limestone, ledge | 22.0 |
| m. Chert concretion bed .. | 4.0 |
| n. Limestone with two thin concretion beds, ledge . | 17.5 |

Toroweap formation, eastern phase:

- | | |
|--|------|
| 1. Sandstone, white, calcareous, fine-grained, crumbly; bedding irregular; weathers to slope, largely concealed | 27.5 |
| 2. Sandstone, red, hard, fine-grained, calcareous; weathers to weak ledge | 5.5 |
| 3. Sandstone, pink to white; gnarly, irregular bedding; series of thick beds, each cross-laminated on small scale; weathers to rounded surface | 88.0 |
| 4. Sandstone, yellow to white; in beds 5-12 feet thick, each cross-laminated; calcareous, crumbly, cliff-forming | 47.5 |
| 5. Sandstone, yellow and red, flat-bedded, calcareous, fine-grained, ledge-forming | 16.5 |

Coconino sandstone:

Typical large-scale (30-40 feet) cross-laminations beveled to flat upper surface; about 100 feet exposed

39. SECTION IN STRAIGHT CANYON AT FOOT OF CEDAR MESA ⁶

Moenkopi formation:

- | | |
|--|-----|
| 1. Shale, red, thin-bedded | |
| 2. Conglomerate, composed of subangular pebbles of quartz, chert, and other resistant minerals in a pink, shaly matrix | 3.0 |

⁶ The divisions in this section do not seem to be clear and are open to question.

Unconformity: Irregular surface of erosion

Kaibab formation:

α member:	Feet
1. Limestone, dull gray, magnesian; weathers to rough, pitted surface; forms ledge; fossiliferous (molds of pelecypods abundant)	12.0
β member:	
1. Sandstone, white, sugary, fine-grained; thin band of dull white chert in middle	18.5
2. Chert, white, dull; forms bed	2.0
3. Sandstone, white to buff, sugary; like no. 1	10.0
4. Chert, white and yellow, brittle; contains tongues of yellow sandstone	18.5
5. Sandstone, yellow, fine-grained, hard, calcareous; contains many geodes	4.0
6. Chert, white, dull; like no. 4	1.0
7. Sandstone, yellow; like no. 5	6.0
8. Chert, white, dull; like no. 4	5.0
9. Limestone, brownish, magnesian; weathers brown with pitted surface in series of ledges; fossiliferous (poorly preserved gastropod and pelecypod molds); becomes slightly sandy above 30 feet and grades upward into cross-laminated white sandstone in top 30 feet .	126.0

Toroweap formation, eastern phase:

1. Sandstone, white grading downward into brown, fine-grained, calcareous; weathers into ledges 5-20 feet thick with gray surface; contains many geodes	158.0
2. Sandstone, red, fine-grained, argillaceous, hard, structureless; weathers to ledge with rough surface	6.0
3. Sandstone, white, sugary, calcareous, strongly cross-laminated; grades upward into flat-bedded pink and white calcareous sandstone	19.5
4. Limestone, dark reddish purple; weathers to rough surface; probably equals β member to west	3.0
5. Sandstone, pink, calcareous, fine-grained; beds each a few feet thick	26.0

Cocconino sandstone (?):

77 feet exposed

40. SECTION ALONG LITTLE COLORADO GORGE NORTH OF CEDAR MOUNTAIN

Moenkopi formation:

1. Shale, red, thin-bedded
2. Conglomerate, highly colored; composed largely of angular chert fragments

Kaibab formation:

α member:	
1. Limestone, gray, magnesian, fairly thin-bedded; contains quartz grains scattered throughout; weathers to ledges with rough, pitted surface	22.0
2. Sandstone, white, sugary, fine-grained; locally cross-bedded	16.5
3. Limestone, gray, magnesian; like no. 1	11.0
4. Sandstone, white, sugary; like no. 2 but more extensively cross-bedded	30.0

	Feet
5. Limestone, gray, magnesian; like no. 1 but without elastic quartz ..	16.5
6. Sandstone, white, fine-grained, ledge-forming, flat-bedded	11.0
β member:	
1. Limestone, gray and brown, massive, ledge-forming; beds 4-6 feet thick, alternating with	
Sandstone, white, sugary, fine-grained; beds 2-4 feet thick; weathers to recess	
Total forms cliff. Limestones contain geodes and iron concretions, weather to pitted, gray surface, above 60 feet. Sandstone more yellow, contains geodes, above 116 feet	250.0
Toroweap formation, eastern phase:	
1. Sandstone, white, fine-grained; bedding gnarly; contains some thin bands of yellow-brown limestone; weathers to cliff	25.0
2. Sandstone, white, fine-grained, sugary, ledge-forming, flat-bedded ..	18.5
3. Sandstone, white, fine-grained, sugary, cross-bedded	16.5
4. Sandstone, red-brown, fine-grained, flat-bedded	1.0
5. Sandstone, white, fine-grained, sugary; each bed (3-4 feet) cross-laminated and ledge-forming	30.5
6. Sandstone, white, fine-grained; bedding gnarly; contains irregular bands and tongues of yellow-brown limestone (2-8 inches) at several horizons and one band (4-20 inches) at 40 feet	55.5
Coconino sandstone	

41. SECTION BELOW DESERT VIEW POINT, GRAND CANYON

Rim of canyon; recent erosion surface

Kaibab formation:

 β member:

1. Chert, red and yellow, hard; weathers to rough, irregular surface; contains tongues and lenses of brown sandstone	16.5
2. Sandstone, white, calcareous, fine- to medium-grained, crumbly; locally a sandy limestone	16.5
3. Chert, white; forms bed	6.0
4. Sandstone, white; like no. 2	11.0
5. Chert, white; like no. 3	2.0
6. Sandstone, white; like no. 2	3.5
7. Quartzite, brown, ledge-forming; upper 1 foot grades into brown sandstone, fine-grained with coarser quartz grains scattered throughout	17.5
8. Chert, white, translucent, hard but brittle	9.0
9. Quartzite, gray, cliff-forming; grades downward into Sandstone, yellow, fine-grained, well cemented, compact	17.5
10. Sandstone, yellow, calcareous, sugary, fine-grained; contains concretions and geodes; weathers to ledges with irregular surface; fossiliferous (molds of mollusks)	24.0
11. Sandstone, yellow, sugary, crumbly; fossiliferous (mollusks)	31.5
12. Sandstone, gray, fine-grained, ledge-forming; shark's tooth found near top	10.0
13. Sandstone, yellow, crumbly, calcareous, fine-grained; bedding irregular; weathers to rough surface; unfossiliferous	9.0

14. Sandstone, yellow, thick-bedded (2-6 feet), fine-grained, locally calcareous; weathers to massive cliff with brown varnish on surface; contains very few concretions; fossiliferous (pelecypod and gastropod molds common at 11 feet and 44 feet)	Feet 44.0
15. Limestone, gray, sandy, massive, cliff-forming; contains hard nodules scattered throughout	5.5
16. Chert, white, hard but brittle; forms recess; contains tongues of yellow sandstone	3.0
17. Sandstone, yellow, slightly calcareous, fine-grained, thick-bedded (4 feet); weathers to massive cliff with gray surface; contains bands of elongated, gray chert concretions; contains many fucoids on bottom surface of each bed	30.0
18. Limestone, yellow, impure, cliff-forming; contains many nodules and concretions in upper half; weathers gray and pitted in lower part	28.5
Toroweap formation:	
α member:	
1. Sandstone, pink, fine-grained; weathers to conspicuous ledge	7.5
2. Sandstone, yellow and red, fine-grained, crumbly; bedding gnarly	27.5
3. Sandstone, white, fine-grained, cross-bedded, ledge-forming, non-calcareous	5.5
4. Sandstone, yellow, gnarly; like no. 2	38.5
5. Sandstone, red, fine-grained, crumbly	11.0
6. Sandstone, white, quartzitic; weathers to ledge with rounded surface	4.0
7. Sandstone, red and yellow, fine-grained, crumbly	3.0
8. Sandstone, white, crumbly; contains tongues of hard brown, finely laminated, calcareous sandstone, locally brecciated	18.5
9. Sandstone, white, fine-grained, cross-bedded, ledge-forming; calcareous cement	18.5
10. Sandstone, yellow, fine-grained, crumbly; bedding gnarly	4.0
β member:	
1. Limestone, yellow, sandy; weathers to cliff with pitted surface; fossiliferous (molds of small mollusks)	18.5
γ member:	
1. Sandstone, white, quartzitic, irregular (three bands) alternating with Sandstone, yellow, calcareous, irregular (two bands)	26.5
2. Sandstone, red and yellow, largely calcareous, slope-forming; fine-grained with coarser grains scattered throughout; cross-bedded on small scale near top	26.5
Coconino sandstone	

42. SECTION ALONG HANCE TRAIL, RED CANYON IN GRAND CANYON

Rim of canyon; recent erosion surface

Moenkopi formation:

1. Shale, red and yellow, sandy, thin-bedded
2. Conglomerate

Unconformity: Erosion channels filled with conglomerate

Kaibab formation:

α member:	Feet
1. Limestone, gray, magnesian; weathers to rough, pitted surface; forms ledge	17.0
2. Sandstone, red, fine-grained, crumbly, slightly calcareous	11.0
3. Limestone, gray, magnesian; weathers to pitted surface; forms ledge; fossiliferous (poorly preserved molds of <i>Bellerophon</i> assemblage)	16.5
4. Limestone, pale gray, very thin-bedded, sandy; contains some chert concretions	9.0
β member:	
1. Chert, light gray, quartzitic, hard, ledge-forming	4.0
2. Sandstone, white, sugary, non-calcareous, slightly cross-bedded; fine-grained but contains some coarse, well-rounded quartz grains scattered near top; grades into chert bed above	10.0
3. Sandstone, yellow, fine-grained, non-calcareous, crumbly; grades upward into chert, red and yellow, ledge-forming (6 feet) and back to yellow, crumbly sandstone	28.0
4. Limestone, white, very sandy, fine-grained; without chert but containing quartz geodes, especially common near top; basal 28 feet thin-bedded and slope-forming, next 18 feet massive and cliff-forming, upper 25 feet thin-bedded and slope-forming except for massive ledge in center	71.5
5. Sandstone, yellow; contains concretions of quartzite and nodules of chert	12.0
6. Limestone, light gray, very sandy, fine-grained, thin-bedded	3.5
7. Sandstone, white; fine-grained with coarser, rounded quartz grains scattered through top portion; prominently cross-bedded (beds 20–25 feet long, with low angle of dip); weathers to ledge with dark gray surface	13.0
8. Sandstone, yellow; like no. 5	26.0
9. Chert, white, hard but brittle; contains tongues and lenses of yellow sandstone; weathers to recess	3.0
10. Sandstone, yellow; contains band of brown quartzitic concretions midway	11.0
11. Chert, white, hard but brittle; like no. 9	2.0
12. Sandstone, yellow, fine-grained, calcareous; contains scattered nodules	6.0
13. Chert, white, hard but brittle; like no. 9	3.0
14. Sandstone, yellow, calcareous, fine-grained; contains numerous zones of white chert like that in no. 7 but poorly developed and in thinner bands; contains scattered chert concretions and a band of large, round, brown, quartzitic concretions	58.5
15. Chert, dull gray; like no. 9	2.0
16. Sandstone, yellow, calcareous, fine-grained; contains scattered chert nodules at a few horizons and several bands of brown, quartzitic concretions (6 inches thick); weathers to massive ledges (5–15 feet) with brown surface; fossiliferous near top (<i>Productus bassi</i>)	45.0

	Feet
17. Chert, dull gray; like no. 9	2.0
18. Sandstone, yellow, calcareous, fine-grained, massive; like no. 16; nodules scattered through upper third; fossiliferous at top (<i>Chonetes kaibabensis</i>)	34.5
Unconformity: Erosion channels filled with overlying sandstone	
Toroweap formation:	
α member:	
1. Sandstone, yellow, non-calcareous, crumbly, cross-bedded; fine-grained with some rounded, coarser quartz grains scattered throughout	8.0
2. Sandstone, white, fine-grained; quartzitic in places, weathers to prominent brown color	0.5
3. Sandstone, yellow, fine-grained, crumbly	2.5
4. Limestone, gray, impure, thin-bedded; weathers to smooth surface	0.5
5. Sandstone, red, fine-grained, crumbly; bedding gnarly	52.0
6. Sandstone, white, fine-grained, cross-bedded, ledge-forming, non-calcareous	6.5
7. Sandstone, red, gnarly; like no. 5	16.5
8. Sandstone, white, cross-bedded; like no. 6	12.5
9. Sandstone, red, gnarly; like no. 5	16.5
10. Sandstone, white, cross-bedded; like no. 6	3.0
11. Sandstone, red, gnarly; like no. 5	26.5
β member:	
1. Limestone, dull gray, thin-bedded, impure; weathers to smooth surface, straight faces, small blocks	2.0
2. Limestone, light gray, slightly sandy, cliff-forming; contains white, sugary sandstone lenses near base; fossiliferous (pelecypod-gastropod assemblage, molds)	52.0
3. Limestone, gray, thin-bedded; like no. 1	1.0
γ member:	
1. Sandstone, red and yellow, calcareous; fine-grained with coarser quartz grains scattered through basal portion; slope-forming below, more massive above	28.0
Cocconino sandstone	

43. SECTION ALONG SOUTH PORTION, KAIBAB TRAIL, GRAND CANYON

(Top 2 beds at Yaki Point; underlying 27 beds west of fault; all others to east)

Rim of canyon; recent erosion surface

Kaibab formation:

α member:

- | | |
|---|------|
| 1. Sandstone, red, very fine-grained, crumbly; weathers to slope | 26.0 |
| 2. Limestone, light gray, fairly thin-bedded; weathers to ledges with rough pitted surfaces except at base, where they are smooth, fossiliferous (<i>Bellerophon</i> assemblage) | 23.0 |

β member:

- | | |
|--|------|
| 1. Sandstone, yellow, fine-grained, ledge-forming | 8.0 |
| 2. Chert, white, hard but brittle; contains tongues and lenses of yellow sandstone; weathers to recess | 4.0 |
| 3. Sandstone, yellow to white, calcareous, cliff-forming; contains chert in bands and in nodules | 13.0 |

Feet

4. Chert, white, hard but brittle; like no. 2	3.0
5. Sandstone, yellow, calcareous, ledge-forming; contains chert in band and in scattered concretions	3.0
6. Chert, white, hard but brittle; like no. 2	11.0
7. Limestone, buff, sandy, cliff-forming; contains chert in bands and in scattered nodules and concretions	15.0
8. Limestone, white, sandy, cliff-forming; contains scattered chert nodules and concretions; fossiliferous (unidentifiable, scarce)	16.0
9. Sandstone, light brown, calcareous, ledge-forming; contains chert nodules and concretions	2.0
10. Limestone, white, massive, cliff-forming; contains many chert nodules and concretions	13.0
11. Limestone, buff, sandy, massive, cliff-forming; contains many chert masses in upper part, some with sponge centers	43.0
12. Chert, white, hard but brittle; like no. 2	3.0
13. Limestone, buff, sandy, cliff-forming; contains chert in nodules and concretions, banded near top	18.0
14. Chert, white, hard but brittle; like no. 2	3.0
15. Limestone, buff, sandy, fairly thin-bedded, ledge-forming; contains a few chert bands and concretions	7.0
16. Chert, white, hard but brittle; like no. 2	3.0
17. Sandstone, yellow, fine-grained, hard; contains some chert; grades downward into quartzite, white to gray, cliff-forming; contains abundant fossils, poorly preserved (<i>Schizodus?</i>)	17.0
18. Chert, white, hard but brittle; like no. 2	4.0
19. Limestone, buff, sandy, massive, ledge-forming; contains a few chert concretions, large fucoids at base	4.0
20. Chert, white, hard but brittle; like no. 2	4.0
21. Limestone, buff, sandy, cliff-forming; contains little chert; fucoids near top	32.0
22. Limestone, buff, sandy, cliff-forming; contains few chert concretions; very fossiliferous (<i>Productus bassi</i>)	16.0
23. Chert, blue-gray, hard but brittle; forms recess	3.0
24. Limestone, buff, sandy, massive, cliff-forming; contains quartzitic concretions and nodules, also fucoids at several horizons; fossiliferous (<i>Chonetes kaibabensis</i> , <i>Productus bassi</i> , erinoids)	21.0
25. Chert, blue; forms irregular bands and tongues; contains lenses of sandstone, yellow, fine-grained; bed forms recess	2.0
26. Chert, gray; forms rounded irregular masses; more resistant than overlying bed	6.0

Toroweap formation:

α member:

1. Sandstone, yellow, fine-grained, friable	18.0
2. Limestone, gray, ledge-forming; very fossiliferous (<i>Schizodus?</i>) ..	3.0
3. Sandstone, yellow, fine-grained, fairly resistant; contains one thin bed of limestone near center	13.0
4. Sandstone, red, fine-grained, crumbly; bedding gnarly	120.0
5. Sandstone, white, cross-bedded, ledge-forming	7.0
6. Sandstone, red, fine-grained, crumbly; bedding gnarly	14.0

β member:	Feet
1. Limestone, gray-brown, fine-grained, massive, cliff-forming; weathers with rough surface; contains thin-bedded, smooth-surfaced limestone beds at base and near top, also thin, brown sandstone beds near top; fossiliferous (abundant but poorly preserved, small, of <i>Bellerophon</i> assemblage)	68.0
γ member:	
1. Sandstone, pink, green, and yellow, fine-grained, crumbly	16.5
2. Sandstone, brown, thin-bedded, hard, ledge-forming; contains a few partings of thin, green shale	16.5
3. Sandstone, pale bluish green, fine-grained, fairly soft	2.0
4. Sandstone, red, very fine-grained with coarser quartz grains scattered throughout basal part; fairly resistant	8.0
Coconino sandstone	

44. SECTION ALONG BRIGHT ANGEL TRAIL, GRAND CANYON, WEST OF FAULT

Rim of canyon; recent erosion surface

Kaibab formation:

 α member:

1. Limestone, gray, magnesian, ledge-forming; weathers to rough pitted surface; fossiliferous (molds of *Bellerophon* assemblage) 4.0
2. Limestone, pale gray, thin-bedded; weathers to smooth surface 8.5

 β member:

1. Limestone, white, sandy; mostly flat-bedded but cross-bedded in part; coarse sand particles scattered through fine matrix; ledge .. 19.5
2. Chert, yellow and red, hard; weathers to rough, irregular surface .. 11.0
3. Limestone, buff, sandy, massive, fossiliferous, cherty in part, alternating with white bedded chert or beds of concretionary chert (details of subdivisions and locations of fossil zones given in figure 24); total thickness

253.0

Toroweap formation:

 α member:

1. Limestone, gray, ledge-forming; very fossiliferous (*Schizodus*?) .. 4.0
2. Sandstone, yellow, fine-grained, fairly resistant; contains one thin bed of limestone near center
3. Sandstone, red and yellow, fine-grained, crumbly; bedding gnarly .. 115.0
4. Travertine, gray, ledge-forming
5. Sandstone, red and yellow, fine-grained, crumbly; bedding gnarly . 13.0
6. Sandstone, white, cross-bedded, ledge-forming
7. Sandstone, red, fine-grained, crumbly; bedding gnarly

12.0

 β member:

1. Limestone, gray-brown, fine-grained, massive, cliff-forming; weathers with rough surface; very thin-bedded limestone with smooth surface at top; fossiliferous (abundant but poorly preserved and small fossils of *Bellerophon* assemblage)

64.5

 γ member:

1. Sandstone, yellow, fine-grained, thin-bedded, crumbly
2. Limestone, gray, thin-bedded, ledge-forming

16.5

5.0

3. Sandstone, red and yellow, very fine-grained with coarser quartz grains scattered throughout basal part; upper part thin-bedded; fairly resistant but containing thin, weak zone in middle	Feet 30.0
Cocconino sandstone	

45. SECTION ALONG HERMIT TRAIL, GRAND CANYON

Rim of canyon; recent erosion surface

Kaibab formation:

 α member:

- | | |
|---|------|
| 1. Limestone, gray, thin-bedded; contains a few molds of mollusks; weathers to ledges with rough surfaces; and
Sandstone, white, calcareous, slope-forming | 41.0 |
|---|------|

 β member:

- | | |
|--|------|
| 1. Chert, red and yellow, hard, ledge-forming | 7.0 |
| 2. Limestone, light gray, fairly thin-bedded; contains a few chert nodules; weathers to ledges | 26.0 |
| 3. Limestone, buff, sandy, massive, cliff-forming; contains abundant chert nodules and concretions; principal fossil subdivisions from top to bottom are: <i>a</i> , 18 feet; <i>b</i> , 27 feet; <i>c</i> , 13 feet; <i>d</i> , 11 feet; <i>e</i> , 13 feet (<i>Productus bassi</i> , <i>a</i> , <i>b</i> , <i>c</i> , <i>d</i> , <i>e</i> ; <i>Waagenoconcha</i> sp., <i>b</i> , <i>c</i> , <i>e</i> ; <i>P. occidentalis</i> , <i>a</i> ; <i>Avonia</i> sp., <i>a</i> , <i>b</i> , <i>c</i> , <i>d</i> ; <i>Squamularia</i> sp., <i>a</i> , <i>b</i> , <i>e</i> ; <i>Chonetes subliratus</i> , <i>b</i> , <i>c</i> , <i>d</i> , <i>e</i> ; <i>Composita</i> sp., <i>d</i> ; <i>Meekella</i> sp., <i>d</i> ; <i>Derbya</i> sp., <i>d</i> , <i>e</i> ; crinoids, <i>a</i> , <i>b</i> , <i>c</i> , <i>d</i> , <i>e</i> ; <i>Lophophyllum</i> sp., <i>a</i> , <i>e</i> ; bryozoa, <i>a</i> , <i>b</i> , <i>c</i> , <i>d</i> , <i>e</i> ; sponges, <i>a</i> , <i>d</i> , <i>e</i>) | 82.0 |
| 4. Chert, gray, bedded, hard but brittle; tongues and lenses of yellow sandstone | 3.0 |
| 5. Sandstone, yellow, very calcareous, cliff-forming; contains chert nodules near base; fossiliferous at top (<i>Productus bassi</i> , crinoids, sponges) | 22.0 |
| 6. Limestone, buff, massive, very sandy, cliff-forming; contains a few chert nodules; fossiliferous (<i>Productus bassi</i> , <i>Avonia</i> sp., <i>Chonetes subliratus</i> , crinoids) | 9.0 |
| 7. Sandstone, yellow, fine-grained, cliff-forming; without chert | 13.0 |
| 8. Chert, white, hard but brittle; contains tongues and lenses of yellow sandstone; weathers to recess | 6.0 |
| 9. Limestone, buff, massive, ledge-forming; contains few chert concretions; fossiliferous (<i>Productus bassi</i> , <i>Squamularia</i> sp., crinoids, bryozoa) | 4.0 |
| 10. Chert, white, hard but brittle; like no. 8 | 4.0 |
| 11. Limestone, buff, sandy, resistant; contains band of chert concretions | 2.0 |
| 12. Chert, white, hard but brittle; like no. 8 | 3.0 |
| 13. Limestone, buff, sandy, massive; contains a few chert nodules | 5.0 |
| 14. Chert, white, hard but brittle; like no. 8 | 3.0 |
| 15. Limestone, yellow-brown, very sandy, massive, ledge-forming; contains large concretions in band near top and scattered throughout; fossiliferous (crinoids, sponges) | 7.0 |
| 16. Chert, white, hard but brittle; like no. 8 | 10.0 |
| 17. Limestone, buff, sandy, massive, ledge-forming; contains scattered chert nodules; fossiliferous (<i>Productus bassi</i>) | 7.0 |

	Feet
18. Sandstone, white, massive, cliff-forming; without chert	19.0
19. Limestone, buff, very sandy, massive, cliff-forming; contains scattered chert nodules throughout	15.0
20. Chert, white, hard but brittle; like no. 8	2.0
21. Limestone, buff, sandy, massive; contains scattered chert nodules .	4.0
22. Chert, white, hard but brittle; like no. 8	4.0
23. Limestone, buff, sandy, massive; contains a few chert nodules near base; fossiliferous (<i>Productus bassi</i> , crinoids, <i>Chonetes kaibabensis</i>)	8.0
24. Chert, white, hard but brittle; like no. 8	5.0
25. Limestone, buff, sandy, massive, cliff-forming; contains quartzitic concretions in bands and scattered; fossiliferous (<i>Productus bassi</i> , <i>Aviculopecten</i> sp., bryozoa, <i>Chonetes kaibabensis</i>)	16.0
26. Chert, white and brown; in irregular masses and in bands; and Sandstone, yellow, fine-grained Fossiliferous (<i>Chonetes kaibabensis</i> and crinoids)	11.0
27. Limestone, buff, massive; contains a few chert concretions	5.0
Toroweap formation:	
α member:	
1. Sandstone, yellow, fine-grained, crumbly; weathers to slope	14.0
2. Limestone, yellow-brown, ledge-forming; fossiliferous (<i>Schizodus</i> ?)	3.0
3. Limestone, yellow, hard, ledge-forming; contains many quartz clastics	3.0
4. Sandstone, red and yellow, crumbly, fine-grained; bedding irregular	60.0
5. Sandstone, white, cross-bedded; forms ledge	2.0
6. Intraformational conglomerate; angular fragments of red sandstone and yellow limestone; distribution local	8.0
7. Sandstone, green and yellow, shaly; weathers to recess	0.5
8. Sandstone, red and yellow, crumbly, fine-grained; bedding irregular	41.0
9. Limestone, blue-gray, thin-bedded, magnesian	0.5
10. Sandstone, yellow, crumbly, fine-grained; bedding irregular	31.0
11. Limestone, gray, thin-bedded, magnesian	2.0
β member:	
1. Limestone, buff, massive, cliff-forming; contains a few chert nodules; fossiliferous (poorly preserved mollusks)	56.0
2. Sandstone, yellow, fine-grained, crumbly	0.5
3. Limestone, buff, thin-bedded, resistant; contains sandstone zone ...	2.0
4. Sandstone, yellow, fine-grained, crumbly	4.0
5. Limestone, yellow, sandy; weathers to slope	11.0
6. Limestone, yellow-brown, massive, ledge-forming	7.0
7. Limestone, buff, very sandy; weathers to slope	10.0
8. Limestone, buff, ledge-forming	3.0
9. Limestone, buff, weathers to slope	4.0
10. Limestone, buff, massive, cliff-forming; fossiliferous (poorly preserved mollusks)	8.5
11. Limestone, buff, thin-bedded; forms recess; zones of white sandstone	1.0
12. Limestone, buff, massive, ledge-forming; fossiliferous (poorly preserved mollusks)	4.0

13. Limestone, buff, thin-bedded, resistant; contains zones of sandstone γ member:	Feet 2.0
1. Sandstone, red, fine-grained with some coarser grains scattered throughout	7.0
Coconino sandstone	

46. SECTION AT FOSSIL MOUNTAIN IN GRAND CANYON

Top of hill; recent erosion surface

Kaibab formation:

β member:

1. Limestone, gray; beds fairly thin; contains chert concretions; weathers to slope and ledges; fossiliferous (bryozoa, <i>Chonetes subliratus</i> , <i>Productus bassi</i> , crinoids, <i>Derbya</i> sp., <i>Composita</i> sp., <i>Aviculopecten</i> sp., <i>Squamularia</i> sp., <i>Ditomopyge</i> sp.)	14.0
2. Limestone, gray; beds fairly thin; contains irregular chert through- out; weathers to slope above, cliff below; fossiliferous (<i>Productus occidentalis</i> , <i>Composita</i> sp., <i>Avonia</i> sp., <i>Lophophyllum</i> sp., crinoids, <i>Meekella</i> sp., <i>Pugnoides</i> sp., <i>Spiriferina</i> sp., <i>Productus bassi</i>)	42.0
3. Limestone, gray; chert concretions and nodules throughout and chert bed at base; fossiliferous (<i>Productus bassi</i> , <i>Avonia</i> sp., bryo- zoa, sponges, crinoids, <i>Derbya</i> sp., <i>Chonetes subliratus</i>)	24.0
4. Limestone, gray; beds fairly thin and irregular; very little chert; fossiliferous (<i>Avonia</i> sp., <i>Productus bassi</i> , bryozoa, <i>Lophophyl- lum</i> sp., <i>Chonetes subliratus</i> , <i>Squamularia</i> sp., <i>Composita</i> sp., <i>Spiriferina</i> sp.)	21.0
5. Limestone, gray, massive, crystalline; contains chert nodules throughout; fossiliferous (crinoids, <i>Productus bassi</i> , <i>Chonetes sub- liratus</i> , <i>Composita</i> sp., <i>Lophophyllum</i> sp., <i>Waagenoconcha</i> sp.) ..	9.0
6. Limestone, yellow, sandy, contains chert nodules and concretions, weathers to slope	6.0
7. Limestone, yellow, sandy, ledge-forming; fossiliferous (crinoids, bryozoa)	0.5
8. Chert, bedded, white; tongues and lenses of yellow sandstone	16.0
9. Limestone, blue-gray, sandy; contains few chert nodules; weathers to slope; fossiliferous (<i>Productus bassi</i> , <i>Chonetes subliratus</i> , <i>Der- bya</i> sp., bryozoa)	5.0
10. Chert, bedded, white; tongues and lenses of yellow sandstone	8.0
11. Limestone, bluish gray, massive, cliff-forming, without chert; fos- siliferous (<i>Productus bassi</i> , <i>Chonetes subliratus</i> , crinoids, bryo- zoa)	8.0
12. Chert, bedded, white; hard but brittle; yellow sandstone tongues ..	5.0
13. Limestone, light gray, massive; weathers to slope and ledge; fos- siliferous (<i>Productus bassi</i>)	6.0
14. Limestone, blue-gray, massive, cliff-forming; without chert; fos- siliferous (<i>Productus bassi</i> , <i>Chonetes subliratus</i> , bryozoa)	4.0
15. Limestone, yellow to gray, sandy, massive, cliff-forming; contains bands of oval concretions	7.0
16. Limestone, blue-gray, massive, crystalline; weathers to ledges with slope between and to brown surface; chert masses scattered	

throughout; fossiliferous (<i>Chonetes kaibabensis</i> , crinoids, trilobite, bryozoa, <i>Productus bassi</i> , <i>Aviculopecten</i> sp.)	Feet 13.0
17. Limestone, light gray, fairly thin-bedded; contains abundant irregular chert masses; fossiliferous at top (crinoids, bryozoa)	12.0
18. Sandstone, yellow, calcareous; weathers to slope; without chert ..	7.0
19. Limestone, yellow to gray, sandy, thin-bedded, ledge-forming; contains bands of chert concretions	4.0
Unconformity: Erosion of channels and angular conglomerates	
Toroweap formation:	
α member:	
1. Limestone, gray, thin-bedded, magnesian; fossiliferous (abundant pelecypods, <i>Schizodus</i> ?)	2.0
2. Sandstone, red and yellow, crumbly; bedding gnarly; weathers to slope mostly covered with talus	87.0
3. Travertine, gray; contains fragments from red beds	1.0
4. Sandstone, red and yellow, crumbly; weathers to slope	41.0
5. Limestone, dark gray, thin-bedded; weathers to receding ledges; contains some red-bed fragments in middle	8.0
β member:	
1. Limestone, light gray, thin-bedded, ledge-forming	3.0
2. Limestone, dark gray, massive, cliff-forming; contains bands of chert nodules	20.0
3. Limestone, dark gray, massive, cliff-forming; without chert; contains poorly preserved molluscan fossil molds	98.0
4. Limestone, gray, very sandy, cliff-forming	12.0
5. Limestone, gray, massive, cliff-forming; fossiliferous (poorly preserved mollusk molds)	5.0
γ member:	
1. Sandstone, buff; fine-grained with coarser quartz grains scattered through lower part; weathers to recess	3.0
2. Limestone, dark gray, thin-bedded; interbedded with thin layers of yellow sandstone; a few poorly preserved mollusks	4.0
3. Sandstone, yellow, crumbly, calcareous	1.0
Coconino sandstone	

47. SECTION AT HILLTOP, NEAR HAVASU CANYON, NORTH SIDE OF VALLEY

Top of hill; recent erosion surface

Kaibab formation:

α member:

1. Limestone, white to brown, fine-grained; contains a few white concretions; weathers to rough, pitted surface with pink staining locally	16.5
2. Concealed interval; probably red bed	16.5
3. Limestone, gray-brown, magnesian; weathers to ledge with rough jagged surface; contains a few casts of <i>Bellerophons</i>	16.5
4. Concealed interval; probably red bed	11.0
5. Limestone, gray, sandy; contains no concretions; weathers to pitted surface	3.0
6. Limestone, white, thin-bedded, magnesian; contains bands of gray chert; weathers to smooth surface and forms slope	5.5

	Feet
β member:	
1. Limestone, gray, slightly sandy; contains brown chert in definite bands and as scattered concretions, also irregular bands of white chert in upper half; weathers to pitted surface and forms two massive ledges; fossiliferous, especially in lower half (<i>Productus bassi</i> , <i>P. occidentalis</i> , <i>Spiriferina</i> sp., abundant crinoids)	41.5
2. Limestone, gray, crystalline, free from elastic sand; contains masses of white chert scattered throughout; brown chert occurs as more or less definite bands, each 6-12 inches thick, accompanied by occasional yellow sandy bands, in upper 83.5 feet (bands more definite toward top), also in scattered places throughout middle 71.5 feet, but not at all in bottom 44 feet; shows gradual transition upward from one chert type to another; weathers to series of ledges forming large cliff in places, to pinnacles in others; highly fossiliferous throughout except in upper very cherty part (<i>Productus bassi</i> , bryozoa, <i>Aviculopecten</i> sp., <i>Chonetes kaibabensis</i> at 16 feet; <i>Productus bassi</i> , <i>Productus occidentalis</i> , <i>Derbya</i> sp., <i>Composita</i> sp., <i>Lophophyllum</i> sp., <i>Avonia</i> sp., <i>Spiriferina</i> sp., <i>Squamularia</i> sp. and bryozoa at 38 feet and in many higher beds)	199.0
3. Sandstone, white, calcareous, thick-bedded; contains a few large concretions; weathers to ledge	14.0
4. Limestone, gray, sandy; contains numerous blue-gray concretions; fossiliferous (<i>Productus bassi</i> , bryozoa, <i>Aviculopecten</i> sp., crinoids, <i>Squamularia</i> sp.)	7.5
5. Limestone, gray, crystalline; contains abundant irregular white patches of chert, otherwise like no. 6; weathers to slope; fossiliferous (<i>Chonetes kaibabensis</i> , <i>Productus bassi</i> , bryozoa)	19.5
6. Limestone, brownish gray; sandy near base, crystalline above; weathers to prominent cliff with gray pitted surface (<i>Chonetes kaibabensis</i> near base and above, <i>Productus bassi</i> near top)	27.5
7. Chert, gray, concretionary; forms thin bands with tongues of yellow sandstone within; grades into underlying beds	3.0
8. Limestone, gray, hard, compact; in 2-foot beds with small round concretions near top of each; weathers to ledge with smooth surface ...	4.0
9. Sandstone, yellow, fine-grained, slightly calcareous; locally a quartzite; fills 6-foot pocket in underlying beds	10.0
Unconformity: Surface of erosion	
Toroweap formation:	
α member:	
1. Gypsum	2.0
2. Dolomite, gray, thin-bedded, hard; contains bands of blue chert; weathers to ledge, some of beds to smooth surface, others to pitted surface; fossiliferous 4 feet above base (<i>Schizodus</i> ?)	11.0
3. Sandstone, yellow, crumbly; fine-grained with coarser grains scattered throughout	3.5
4. "Breccia," limestone-gypsum	2.0
5. Limestone, gray, thin-bedded, impure; bedding irregular	1.0
6. Gypsum	9.0
7. Sandstone, red, fine-grained, crumbly; forms slope	7.5

	Feet
8. Gypsum	13.0
9. Sandstone, red, fine-grained, crumbly; forms slope	15.5
10. Gypsum	6.5
11. Sandstone, red, fine-grained, crumbly; contains 3-inch gypsum bed about 4 feet above base	12.0
12. Gypsum; contains some impure, dark gray dolomite near base	5.0
13. Sandstone, red, fine-grained, crumbly; forms slope	8.5
14. Gypsum	8.0
15. Sandstone, red, fine-grained, crumbly; forms slope	10.0
16. Gypsum	13.0
17. Sandstone, red, fine-grained, crumbly; forms slope	14.0
18. Gypsum	22.0
19. Sandstone, red and yellow, fine-grained, crumbly, irregularly bedded; forms slope	15.0
20. Dolomite, pale gray, thin-bedded; weathers to smooth face	12.0
21. Gypsum	3.0
22. Dolomite, gray, impure, thin-bedded	11.0
β member:	
1. Limestone, gray, hard; weathers to ledges with rough surface	16.5
2. Limestone, gray, hard; resembles no. 1 but beds thicker and form massive cliff; fossiliferous (<i>Productus ivesi</i> , 10-25 feet up)	49.5
3. Dolomite, gray to yellow, thin-bedded (2-6 inches), hard; forms ledges; fossiliferous (<i>Bellerophon</i> sp., 11 feet up)	44.0
4. Limestone; yellow, massive beds weathering to rough surfaces, alternating with gray, hard, smooth beds (2-4 feet thick); locally fossiliferous (<i>Bellerophon</i> sp.)	15.5
5. Sandstone, yellow, fine-grained, calcareous, crumbly; bedding ir- regular	1.0
6. Dolomite, dark gray, impure, thin-bedded, hard but brittle	8.5
7. Sandstone, yellow, crumbly; like no. 5	5.0
8. Limestone, yellow and gray, hard; weathers to ledges; beds aver- age 1 foot thick; quartz elastics scattered throughout; fossiliferous	27.5
9. Limestone, yellow, sandy; weathers to rounded ledges	11.0
10. Limestone, yellow, hard but brittle	5.0
γ member:	
1. Sandstone, red, lavender, and yellow, fine-grained with coarser grains throughout; hard near base but friable above	19.5
Cocconino sandstone	
49. SECTION ON EAST SIDE OF TOROWEAP VALLEY, ABOUT 9 MILES ABOVE MOUTH	
Top of hill; recent erosion surface	
Kaibab formation:	
α member:	
1. Limestone, yellow, sandy; forms resistant ledges; very full of white and brown nodules	12.0
2. Concealed interval; probably red sandstone	22.0
3. Limestone, yellow, impure, hard but brittle; beds very thin, irregu- lar; weathers to ledge with wavy upper surface	2.0
4. Sandstone, red, coarse-grained	1.0

	Feet
5. Limestone; like no. 3	3.0
6. Sandstone, red and yellow, and Gypsum	83.5
(Nos. 1-6 may belong to Moenkopi formation; no fossils found)	
7. Limestone, light gray, cherty, very fossiliferous (<i>Productus bassi</i> , bryozoa, erinoids, <i>Composita</i> sp., <i>Euomphalus</i> sp.); uppermost 3 feet largely white chert without fossils	37.0
8. Gypsum, and Sandstone, red	44.0
9. Limestone, dark gray; weathers to smooth surface; grades down- ward into gypsum	11.0
10. Gypsum, and Sandstone, red	59.0
11. Limestone, black; locally contains a breccia of gypsum; ledge- forming, fossiliferous (pelecypods and gastropods)	3.0
12. Limestone, light gray; forms ledge continuous with overlying one	2.0
13. Gypsum; grades downward into cherty limestone	35.0
β member:	
1a. Limestone, gray, crystalline, massive and resistant; black concre- tions abundant, in upper part forming narrow bands which weather to recesses; very fossiliferous in middle (<i>Archæocidaris</i> and <i>Pro- ductus occidentalis</i>)	40.5
1b. Limestone, light gray, crystalline; massive and resistant above, thin-bedded below; weathers to recess below; full of round, white concretions; very fossiliferous (<i>Productus bassi</i> , <i>Marginifera me- ridionalis</i> , <i>Pugnoides</i> sp., bryozoa, erinoids, horn corals, <i>Derbya</i> sp.)	75.0
2. Limestone, gray; beds thick and massive; full of gray and brown chert nodules and concretions; weathers to a massive cliff and “pillars of erosion”; fossils scattered throughout, often in concre- tions (erinoids, <i>Chonetes kaibabensis</i> at base; <i>Productus bassi</i> at 16 feet; large <i>Aviculopecten</i> sp., <i>Derbya</i> sp., <i>Chonetes kaibabensis</i> at 38 feet; <i>Avonia</i> sp., bryozoa, <i>Marginifera meridionalis</i> at 77 feet)	137.5
3. Limestone, light gray; beds thin, flaky	4.0
Toroweap formation:	
α member:	
1. Gypsum, bedded, and Sandstone, red, fine-grained, and Shale, black, thin, and Limestone, gray, impure, thin-bedded; weathers to smooth surface .	182.0
2. Limestone, light gray, thin-bedded; weathers to small blocks and smooth surface	7.5
β member:	
1. Limestone, gray, thick-bedded; weathers to two rounded ledges; white chert nodules abundant; very fossiliferous (same species as in no. 2)	8.0
2. Limestone, light gray, brittle, thin-bedded, contains numerous round, brown concretions; weathers to ledges and recesses; fos- sils abundant but poorly preserved (erinoids, bryozoa, <i>Produc- tus ivesi</i> , <i>Composita</i> sp.)	10.0

3. Limestone, gray, crystalline; weathers to cliff; fossiliferous (same species as in no. 4)	Feet 36.0
4a. Limestone, gray, thick-bedded; weathers to slope; contains irregular bands of blue to white chert concretions; fossiliferous (<i>Archæocidaris</i> sp., crinoids, <i>Productus ivesi</i>)	34.0
4b. Limestone, gray; cliff-forming; without chert bands; fossils same as in no. 4a but fragmentary	43.0
4c. Limestone, gray; contains bands of elliptical chert concretions; fossiliferous near base	8.0
4d. Limestone, gray; weathers to very rough surface; very fossiliferous (same species as in nos. 4a and 4b)	12.0
5. Limestone, gray, hard, locally sandy; beds 2-4 feet thick; weathers to resistant cliff; fossiliferous (same species as in no. 4)	54.0
6. Limestone, gray, sandy; weathers to recess under main cliff; fossiliferous (<i>Productus ivesi</i>)	6.0
7. Chert, blue, bedded, slightly calcareous; weathers to thin ledges ..	7.5
γ member:	
1. Sandstone, white, calcareous, fine-grained with medium-grained quartz fragments throughout, crumbly; bedding irregular; upper part contains breccia of bluish chert	7.0
2. Limestone, brown, thin-bedded	1.0
3. Sandstone, yellowish, fine-grained, sugary, calcareous; bedding nearly horizontal; weathers to rounded surface, usually covered with talus	8.5
Coconino sandstone	

51. SECTION 2 MILES NORTH OF POINT IMPERIAL, GRAND CANYON

Rim of canyon; recent erosion surface; chert fragments from upper part of Kaibab abundant

Kaibab formation:

β member:

1. Sandstone, reddish brown to white, non-calcareous, fine-grained, uniform-grained, friable; weathers to series of ledges; few concretions; fossiliferous at 82 feet above base (molds of gastropods and pelecypods), facies 3 types	143.0
2. Chert, gray, bedded; contains tongues of yellow sandstone	2.0
3. Sandstone, buff, very calcareous; weathers to massive ledges of gray color; contains large, spherical quartzitic concretions with fossil molds, near base	17.0
4. Chert, gray, bedded; like no. 2	3.0
5. Sandstone, gray, very calcareous; resembles no. 3; weathers into two massive, gray ledges; contains hard brown nodules and spherical chert concretions	17.0
6. Chert, gray, bedded; like no. 2	8.0
7. Limestone, gray-brown, sandy; weathers to rough surface; contains hard, brown spherical chert concretions	3.0
8. Sandstone, yellow, non-calcareous, fine-, uniform-grained, irregularly bedded; forms ledge	17.5

9. Limestone, pale lavender to white; weathers to blocks with straight smooth faces; fossiliferous (outlines of indeterminable brachiopods, cf. <i>Composita</i>)	Feet 3.0
10. Sandstone, salmon-colored, calcareous, fine-grained, cross-laminated; weathers to ledge with black face; laminations short, steep .	5.0
11. Sandstone, yellow, calcareous, fine-grained with coarser well-rounded quartz grains scattered throughout, friable; weathers to slope	2.0
12. Limestone, gray and tan, magnesian; contains curving, irregular laminae giving reeflike structure; forms ledge	2.0
Toroweap formation (the four or five beds above may belong to this formation):	
α member:	
1. Sandstone, yellow, crumbly; weathers to rounded ledges	6.5
Concealed, probably red sandstone	5.0
2. Sandstone, red to white, uniform-, fine-grained, irregularly bedded; upper part massive, resistant, and mostly white, lower part sugary, crumbly, mostly red	89.0
3. Sandstone, red and yellow, poorly sorted, very calcareous, crumbly, gnarly, and irregularly bedded; weathers to slope and probably grades into overlying unit	60.5
β member:	
1. Limestone, light gray, hard, cliff-forming, locally sandy; fossiliferous (molds of pelecypods) throughout	61.0
2. Sandstone, yellow, fine-grained, very calcareous, sugary, massive ..	13.5
3. Limestone, brown to dark gray, thin-bedded, brittle; very fossiliferous (molds of pelecypods and gastropods)	3.0
4. Sandstone, yellow; like no. 2	3.0
5. Limestone, brown to dark gray; like no. 3; fossiliferous; locally sandy; appears to grade downward into red beds	16.5
γ member:	
1. Shale, deep red, calcareous, massive, flat-bedded	13.5
Coconino sandstone:	
Typical large-scale cross-laminations, truncated to flat upper surface	
52. SECTION IN MARBLE GORGE OPPOSITE BADGER CANYON, ARIZONA	
Moenkopi formation:	
1. Shale, red, thin-bedded; resting directly on eroded Kaibab surface in places	
2. Conglomerate, angular; composed of white chert, average size 2 inches, rarely 4 inches, from Kaibab formation, in matrix of coarse, buff sandstone; fills shallow erosion cuts in Kaibab	5.0-15.0
Unconformity: Relief in erosion channels up to 15 feet	
Kaibab formation:	
β member:	
1. Chert, white, hard, bedded, and Limestone, yellow, massive; in lower part chert and quartz form large proportion, in upper part compose entire mass; sandy limestone with current ripple marks occurs by gradation above chert, where not removed by erosion	19.0

2. Limestone, buff, sandy; contains abundant white, scattered, irregular concretions; fossiliferous (molds of brachiopods, largely changed to geodes, includes <i>Productus bassi</i> , <i>Composita</i> , <i>Chonetes</i> , crinoids) .	Feet 24.0
3. Limestone, yellow, sandy, massive; contains many geodes, quartz and iron aggregates, and small white nodules scattered throughout	11.0
4. Limestone, light gray to buff, sandy; contains bands of spherical concretions with sponge centers in upper 15 feet; crinoid joints common in limestone and chert margins	19.0
5. Limestone, buff, massive; fossiliferous (<i>Solenomya</i> sp. very common, silicified)	3.0
6. Sandstone, gray, calcareous, crumbly; contains many quartz aggregates; weathers to recess	2.5
7. Limestone, buff; beds 1-3 feet thick; weathers to rough, brown, pitted surface; fossiliferous (molds of large <i>Bellerophon</i> , crinoid joints)	10.0
8. Limestone, gray, fine-grained, cliff-forming; texture uniform; thin chert beds throughout; basal beds thin, irregular owing to underlying surface of relief, main beds 10-15 feet thick; fossiliferous (molds of mollusks)	155.0
a. Limestone	16.0
b. Chert, white, bedded, brittle	2.0
c. Limestone, with <i>Bellerophon</i> and <i>Euphemus</i> at base	12.0
d. Zone of concretions, large, irregular to spherical, light gray, slightly calcareous, hard	0.5
e. Limestone, thin-bedded	2.0
f. Zone of concretions, large, irregular	2.0
g. Limestone, with <i>Bellerophon</i> and <i>Euomphalus</i> common near top; two thin concretionary chert bands below	36.5
h. Zone of chert nodules, white, long, narrow, sometimes branching; contains crinoids	2.0
i. Limestone, with crinoids	18.0
j. Zone of chert nodules, white, small; contains crinoids	1.0
k. Limestone	3.0
l. Zone of chert concretions, large, irregular	0.5
m. Limestone	14.0
n. Zone of chert concretions, white, large, spherical	4.0
o. Limestone	6.5
p. Red chaledony	1.0
q. Limestone, massive, barren	17.0
r. Zone of chert nodules, white, elongated	5.0
s. Limestone, thin, irregularly bedded	14.0
9. Sandstone, chocolate brown, fine-grained, arenaceous, non-bedded; occurs as filling in pockets of underlying quartzite	0-6.0
Unconformity: Erosion surface showing maximum relief of 26 feet; conglomerate of boulders and pebbles in top of salmon quartzite	
Toroweap formation:	
1. Sandstone, white to salmon, locally quartzitic, calcareous in part, massive; beds gnarly, 4-6 feet thick; contains	
Mud rock, deep red, irregularly bedded, slightly calcareous, occur-	

ring as beds and lenses throughout; total forms massive cliff, red-brown on surface; contains lens of gray limestone 55 feet above base	121.0-147.0	Feet
2. Limestone, dull gray, crystalline; beds average 2 feet thick; weathers to ledges with red surface	6.5	
3. Sandstone, white, calcareous; medium-grained quartz scattered throughout; weathers to small, rounded ledges with brown surface	3.0	
4. Limestone, dull gray, crystalline; like no. 2	4.0	
5. Sandstone, variegated red-brown and green, fine-grained, hard, calcareous; beds 1-3 feet thick; weathers to red cliff	8.0	
6. Sandstone, yellow, very fine-grained, hard, slightly calcareous, cross-laminated on small scale; weathers to cliff with smooth straight face and desert varnish	16.0	
7. Sandstone, salmon, hard, flat-bedded, slightly calcareous; medium-sized quartz grains scattered among very fine grains; weathers to black, rounded surface	4.5	
8. Sandstone, yellow, cross-laminated, sugary, thin-, flat-bedded; white quartz grains poorly sorted	9.0	
9. Sandstone, red, slope-forming; contains medium-sized quartz grains scattered through fine matrix; corresponds in detail to basal Toroweap bed throughout Grand Canyon	17.0	

Coconino sandstone:

Typical large-scale cross-lamination, truncated to flat upper surface

59. SECTION IN CANYON 4 MILES SOUTH-SOUTHWEST OF OHIO OIL COMPANY
WELL, CIRCLE CLIFFS, UTAH

Moenkopi formation:

Sandstone, red, massive, ledge-forming; weathers full of cavities and large hollows

Kaibab formation:

 α member:

1. Conglomerate, intraformational; composed of yellow limestone full of subangular pebbles of white quartz and chert, mostly 0.125-0.25 inch in diameter but up to 2 or 3 inches, oriented in all directions, occasionally well rounded; weathers to weak ledge often concealed . 23.0
2. Limestone, yellow-brown; beds 0.5 foot thick; weathers to ledges with rough, pitted surface; contains iron concretions and quartz geodes
3. Limestone, pale yellow; beds 0.5 foot thick; weathers to slope with rough but not pitted surface; conglomeratic near top with a few subangular quartz and chert pebbles

 β member:

1. Limestone, white, fine-grained, thin-, flat-bedded; weathers to slope with smooth surface
2. Limestone, buff, fine-grained, sandy, massive; weathers to prominent ledge with rough surface; white, bedded chert zone in center forms recess; white concretions and geodes above
3. Limestone, buff, sandy; beds 0.5 foot thick; weathers to series of receding ledges with rough, gray surface; contains dendrites, particles of glauconite near top

4. Sandstone, yellow, calcareous, crumbly, thick-bedded; quartz grains fine to medium; weathers to very rough surface; fossiliferous (pelecypods very common but poorly preserved, <i>Productus bassi</i> present)	Feet 6.5
5. Limestone, buff, massive; sandy at base, less above; weathers to cliff with rough, gray surface; dendrites common; fossiliferous (molds of <i>Productus bassi</i> at base)	14.5
6. Sandstone, white, non-calcareous, gnarly, massive, sugary; contains medium-grained quartz scattered through very fine-grained quartz; weathers white and with rounded surface	Exposed 11.0
Canyon bottom	

61. SECTION IN CANYON SOUTHWEST OF THE PEAKS, CIRCLE CLIFFS, UTAH

Moenkopi formation:

Shale, red and yellow, sandy; eroded to slope

Unconformity

Kaibab formation:

 α member:

- | | |
|---|------|
| 1. Limestone, yellow-brown; weathers to resistant ledge capping canyon; surface pitted; contains a few chert pebbles near base, abundant irregular iron masses above; corresponds to no. 2 of α member in section 59 | 16.0 |
| 2. Conglomerate, intraformational; composed of yellow limestone full of subangular to rounded pebbles of white quartz and chert, mostly under 1 inch diameter but up to 2 inches; weathers to weak ledge with pitted surface; corresponds to no. 3 of α member in section 59 | 5.0 |

 β member:

- | | |
|--|------|
| 1. Limestone, yellow, very fine-grained, massive; contains thin beds of white, brittle chert (4-6 inches thick) which form recesses throughout; contains quartz geodes and small round, gray concretions; upper 8 feet grades into intraformational conglomerate with subangular, unoriented chert fragments, 1-2 inches diameter, often crowded together in the limestone | 36.5 |
| 2. Limestone, yellow, sandy in part, porous; weathers to slope or series of weak ledges with rough surface; contains many geodes; beds thin (6 inches) except 2-foot cap; fossiliferous (poorly preserved <i>Spirifer pseudocameratus</i> , <i>Productus</i> sp., bryozoa) | 12.0 |
| 3. Sandstone, white to cream, calcareous, thin-, flat-bedded, uniform-, fine-grained; weathers to slope below, ledge above, with light gray pitted surface | 5.5 |
| 4. Limestone and sandstone, alternating beds, form one massive cliff with beds 3-10 feet thick | 54.5 |
| a. Limestone, buff, very sandy; weathers to pitted surface; fossiliferous (<i>Schizodus</i> , <i>Nautilus</i>) | 16.5 |
| b. Sandstone, white, slightly calcareous, gnarly; contains angular fragments of a darker sandstone; gradational above and below | 11.0 |
| c. Limestone, buff, sandy; weathers pitted; lensing and gradational | 3.0 |
| d. Sandstone, white, slightly calcareous, fine-grained; flat-bedded at bottom, gnarly and brecciated above | 7.0 |

e. Limestone, buff, slightly sandy, massive; weathers rough and pitted, light gray; fossiliferous (molds of pelecypods) 17.0
Cedar Mesa (?) sandstone:

Sandstone, white, sugary, cross-laminated on small scale, gnarly; quartz grains small to medium, rounded, kaolin fairly common; non-calcareous; weathers gray Exposed 5.0

68. SECTION 9.5 MILES SOUTH OF WICKIUP, SECTION 33, TOWNSHIP 23 S., RANGE 11 E., SAN RAFAEL, UTAH

Moenkopi formation:

Shale, yellow (no conglomerate present)

Unconformity: Assumed

Kaibab formation:

α member:

1. Limestone, gray; beds thick in lower part but very thin (6 inches) near top; weathers pitted, brown; fossiliferous (many molds of mollusks, including *Euphemus*) 45.0

β member:

1. Limestone, buff, friable, cavernous, massive; beds 4-8 feet; contains chert nodules with sponge centers; weathers rough, gray or brown; fossiliferous (*Squamularia*, *Waagenoconcha*, *Spirifer pseudocameratus*) 13.5

2. Shale, green and yellow, thin, sandy 7.0

Cedar Mesa (?) sandstone:

1. Sandstone, yellow, flat- or gnarly-bedded; weathers with rounded knobs 3.5

2. Sandstone, white, highly cross-laminated, fine-grained, slabby, friable; forms main cliff

70. SECTION 0.5 MILE WEST OF MOUTH, BLACK BOX CANYON,
SAN RAFAEL SWELL, UTAH

Moenkopi formation:

Conglomerate

Unconformity: Evidence of erosion

Kaibab formation:

α member:

1. Limestone, pale gray, massive; weathers to very pitted, black and brown surface; fossiliferous (molds of gastropods and pelecypods, *Composita*, horn coral) 13.0

β member:

1. Limestone, yellow, massive; weathers to gray, pitted ledge, much silicified on surface; fossiliferous (*Waagenoconcha*, *Spirifer pseudocameratus*, *Squamularia*) 7.5

2. Limestone, buff, thin-bedded, slabby; surface covered with fucoids and geodes 2.0

3. Limestone, tan; contains many geodes, weathers black 7.0

Concealed 5.0

Unconformity: Evidence of warping and erosion

Cedar Mesa (?) sandstone:

1. Sandstone, white to red, sugary, flat-bedded, fine-grained 15.5

- 2. Sandstone, white, cross-laminated on large scale; cliff-forming; several hundred feet exposed

71. SECTION AT EAST END, BLACK BOX CANYON, SAN RAFAEL SWELL, UTAH

Moenkopi formation:	Feet
Conglomerate; contains angular fragments of chert and quartz, white and bluish, commonly 2 inches in diameter, occasionally 6 inches	22.0
Unconformity: Evidence of beds removed by erosion	
Kaibab formation:	
β member:	
1. Sandstone, yellow, argillaceous, non-calcareous; medium-sized clastics in fine-grained matrix	6.5
2. Limestone, gray, thin-bedded; contains fine quartz grains and mica flakes; weathers pale brown	4.5
3. Sandstone, yellow, calcareous, fine-, uniform-grained; bedding gnarly	11.0
4. Limestone, tan, fine-grained, hard; full of white geodes which weather black; rock weathers with tan color	5.0
5. Sandstone, white and yellow, friable; bedding gnarly; medium-sized clastics scattered through fine sand; weathers to slope largely concealed	12.5
Unconformity: Evidence of warping and erosion	
Cedar Mesa (?) sandstone:	
1. Sandstone, yellow, friable, flat-bedded, weathers brown	17.0
2. Sandstone, white to yellow, highly cross-laminated; contains medium-sized quartz grains, much kaolin; weathers yellow, red, black; cliff-forming	

72. SECTION ON WEST FRONT OF MINERAL MOUNTAINS, EAST OF MINERSVILLE, UTAH

Moenkopi formation (only basal portions recorded):	
1. Limestone, blue-gray; weathers to rough, gray ledge; contains abundant fossils including <i>Meekoceras</i> sp.	
2. Shale and fine sandstone, red, thin-bedded	
Kaibab formation:	
α member:	
1. Limestone, brownish gray, fine-grained; weathers to pitted, mouse gray surface; very fossiliferous (poorly defined molds of mollusks)	9.0
2. Limestone, reddish, fine-grained; weathers with hard, black quartzitic varnish	5.5
3. Limestone, light gray, fine-grained, magnesian; weathers pitted ...	28.0
β member:	
1. Chert, white, ledge-forming; brecciated in places	9.0
2. Limestone, blue-gray, crystalline, thin-bedded; weathers into ledges, buff, smooth	106.0
3. Limestone, light gray, crystalline; weathers to massive cliff; very fossiliferous (crinoids, <i>Productus bassi</i> , <i>Composita</i> , <i>Pugnoides</i>); cherty near base	180.0

Toroweap formation:

α member:	Feet
1. Quartzite and siliceous limestones, thin-bedded, weather to slope ..	80.0
2. Limestone, gray, massive; locally forms cliff, contains much brown chert	55.0
3. Quartzite, gray; weathers brown	20.0

 β member:

1. Limestone, light to medium gray; moderately resistant and cliff-forming; contains some brown chert, zone at 200 feet, nodules elsewhere; fossiliferous (crinoids, <i>Productus ivesi</i> at 150 feet)	346.5
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Unassigned Paleozoic:

Quartzite, white to straw-colored, cross-laminated on large scale, hard, locally cliff-forming; individual laminae thin with flat faces, preserving fossil footprints in some cases	Exposed 143.0
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100. SECTION IN SPRING MOUNTAINS, NEVADA, AT TOWN OF GOODSPRINGS

Moenkopi formation

Kaibab formation:

 β member:

1. Limestone, buff; almost made up of irregular masses of black and brown chert, some appearing as a surface varnish, some as brecciated fragments, some as irregular bands and lenses; total massive, cliff-forming	176.0
2. Limestone, gray, massive, crystalline, crinoidal	8.5

Toroweap formation:

 α member:

1. Siltstone or mudrock, red, weakly bedded, crumbly, slope-forming ..	13.0
2. Limestone, gray; weathers to smooth surface, straight face; thin-bedded	6.0
3. Siltstone or mudrock, red, like no. 1	36.0

 β member:

1. Limestone, light gray, massive, coarsely crystalline; fossiliferous (<i>Productus ivesi</i> , crinoids); bands of brown, oval chert scattered throughout; top 11 feet very heavily banded with dark chert; cliff-forming	159.5
2. Limestone, buff, fine-grained, sandy, thick-bedded; contains brown chert nodules	14.0
3. Siltstone or mudrock, red, crumbly, slope-forming	15.5
4. Limestone, light gray, massive, coarsely crystalline; like no. 1; fossiliferous (<i>Productus ivesi</i> , crinoids, <i>Meekella</i> sp., bryozoa, <i>Archæocidaris</i> sp., <i>Composita</i> sp.)	45.0

Hermit (?) shale:

Siltstone, red, crumbly

SUMMARY

The uppermost Permian strata over most of northern Arizona, southern Utah, and southern Nevada—formerly known as the Aubrey limestone and later as the Kaibab limestone—are found to consist in typical exposure of two massive limestone members, above and below each of which are units composed of red beds, gypsum, and impure, thin-bedded limestones. Since these two sequences of sediments represent separate advances and retreats of the sea over a wide area, since the massive limestones within them contain distinctive marine faunas, and since evidence of a widespread, though not great, unconformity has been found at the top of the middle red-bed member, it seems desirable to consider each series as representing a formation.

In view of the complex conditions cited above it is proposed that the name Kaibab be restricted to the upper massive limestone together with associated members above and below, and that these be termed Kaibab formation rather than Kaibab limestone, in order to convey a true picture of the variety of lithology represented. For the three members below the unconformity, which likewise represent deposits of an advancing and retreating sea, the name Toroweap formation is suggested. It is taken from Toroweap Valley, Arizona, where the type section of the formation is well exposed.

Detailed studies of the lateral variations found in each of the members of the Toroweap and Kaibab formations have demonstrated the desirability of recognizing facies based on the lithology and faunas in each. Such facies have been designated by numbers and are discussed in considerable detail, especially as regards the environment which each represents.

In the massive limestone member of the Toroweap formation lateral changes from west to east or from the open sea toward the shore consist of a decrease in thickness, an increase in both elastic sand and magnesium content, and a replacement of the molluscoïd fauna by one of mollusks. In the Kaibab formation the massive limestone member shows corresponding variation in fauna and composition from west to east, but differs in other respects. It extends considerably farther east, especially on the Mogollon Plateau, and maintains a fairly uniform thickness over most of the region of exposure. Several more facies are recognized in it than in the Toroweap, including one containing bedded cherts and another composed entirely of clastic sand.

The nonmarine members of the Toroweap and Kaibab formations—formed before and following the maximum advances of the sea—show, in general, the following lithologic types from west to east: (1) structureless red beds (mostly mud and silt) with gypsum deposits and thin-bedded, magnesian limestones; (2) structureless red beds (silt and sand); (3) light-colored sandstones much cross-laminated on small scale (water types); (4) light-colored sandstones cross-laminated on large scale (æolian type). Not all the red-bed members today show the light-colored sandstone equivalents

to the east, but, were the extensions of these deposits still observable, it seems probable that a type of gradation comparable to that established for other members would appear.

Evidence regarding the general environment of the region during the time of Toroweap and Kaibab deposition leads to the conclusions that the climate was semi-arid or arid, that the sea was very shallow, and that the surrounding terrain was flat and featureless over a vast area. It seems reasonably certain that a relative movement of the sea level of only a few feet was sufficient to allow inundation or retreat of the sea over many miles.

Detailed studies of the various types of sediments included in the Toroweap and Kaibab formations have led to the following conclusions:

1. The relatively pure, coarsely crystalline limestones were formed by a secondary growth of calcareous deposits laid down in the open seas, presumably by organic processes, at considerable distances from shore.

2. The dolomitic limestones were formed in near-shore and lagoonal environments, with dolomitization occurring as a secondary process among unconsolidated sediments.

3. Certain thin-bedded, fine-, uniform-grained limestones occurring as transition stages between red beds and marine limestones and also in association with gypsum deposits are interpreted as chemical precipitates.

4. The gypsum deposits are the product of evaporation in playas or landlocked embayments.

5. The red beds derived their color at the place of origin and retained it wherever sufficient mud and silt remained in the deposits that were spread out in the arid or semi-arid basins of accumulation.

6. The numerous local "breccias" throughout the red-bed series are considered to be intraformational conglomerates.

7. The cherts are thought to be largely a phenomenon of the sea floor, developed by pene-contemporaneous replacement. The silica is believed to have been supplied to the sea by rivers and, depending on local conditions, was either laid down in beds or developed into concretionary forms around sponges and other nuclei.

The marine fauna of the Toroweap formation is not yet well enough known for critical analysis. The fauna of the Kaibab is better known, however, and most of its brachiopods are described in this monograph. On the basis of them, it seems quite definitely established that the Kaibab is to be correlated with the upper part of the Leonard formation of Texas, hence is of Middle Permian age. Furthermore, the Kaibab is believed to be the equivalent of the San Andres limestone of New Mexico, the Chiricahua of southern Arizona, and probably also the Phosphoria of Utah, Idaho, and Wyoming, although the latter undoubtedly represents an unusual environment with most of its fossils highly specialized in character. In brief, it is believed that the Kaibab was deposited in part of a great Middle Permian seaway which extended from west Texas westward along the Mexican border to western Arizona, thence northward through the Great Basin region into Canada and Alaska.

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PART II

SYSTEMATIC DESCRIPTION OF BRACHIOPODS

Rhipidomella transversa King

(Plate 43, figure 1)

1930 *Rhipidomella transversa*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 44, pl. 1, figs. 12, 13.
Hess formation, Leonard formation, Glass Mountains, Texas.

Description. Shell very small, transversely subovate, greatest width about mid length, wider than long, anterior margin rounded.

Ventral valve with cardinal area about half as high as wide, evenly curved upward toward tip at obtuse angle to plane of shell margin; delthyrium narrow; beak incurved. Dorsal valve with cardinal area less than half as high as that on ventral; beak incurved.

Surface marked by even liræ, 2 to 3 in the space of 1 mm. near the anterior margin. The narrow radial liræ are separated by much wider striæ.

Measurements. Specimens (in millimeters):

Specimen	Length	Width	Height of ventral area
King's no. 1.....	10	12	2
King's no. 2.....	9	11	....
Fossil Mountain.....	4.5	6	1

Discussion. Although this species is represented by only one specimen in the Grand Canyon collection and this one is small, the writer has very little hesitation in making this assignment since the specimen is excellently preserved and, except in size, fits King's description well.

Locality and horizon. Middle of β member, Kaibab formation, Fossil Mountain in Grand Canyon.

Meekella occidentalis (Newberry)

(Plate 43, figures 2, 3)

1861 *Streptorhynchus occidentalis*. Newberry, *Report upon the Colorado River of the West, explored in 1857-58 by Lieut. J. C. Ives*, pt. 3, p. 126, pl. 1, figs. 5, 5a. Refigured by Hall and Clarke, *Palæont. of New York*, vol. 8, pt. 1, p. 264, pl. 11B, figs. 18, 19, 1892.

Cherty (Kaibab) limestone, top of Carboniferous series, Camp 73, in canyon of Cascade River.

Description. "Shell depressed, broadly rounded; cardinal border nearly equal to greatest diameter; ventral valve flattened and slightly concave toward anterior margin; beak produced and generally twisted laterally. Cardinal area twice as broad as high; cardinal notch forming a triangle of which the base is half the height; dorsal valve slightly arched throughout; surface bearing 11 to 13 strong radiating costæ, which are striated near the anterior margin." (From Newberry.)

Measurements. Type specimens (in millimeters):

Specimen	Length	Width	Depth	Area (length)	Area (depth)	Delthy- rium	Costæ
U. S. N. M. 92469.....	52	62	22	30	16	9	12
U. S. N. M. 92468.....	46	48	....	25	13	8	12

Discussion. Newberry's description is quoted above since it adequately describes the material which he had. The writer has reexamined the holotype (U. S. N. M. 92468) and also another specimen which presumably was studied, although not figured, by Newberry (U. S. N. M. 92469), so is probably a paratype. Strangely enough, no new specimens that can be considered the same have been found, although search has been made near the type locality. The nearest approach in the Grand Canyon collection is FK-490, which seems to be intermediate between *Meekella occidentalis* and *M. pyramidalis* in general shape and degree of flattening. Length of dorsal valve, 48 mm.; width, 54 mm.; depth, 25 mm.; area (length), 22 mm.; costæ, 11. In other characteristics it is within the range of variability of both forms. For this reason and others given under *M. pyramidalis*, the writer questions the validity of the species, but retains it at least until further material can be obtained to show whether its extreme flatness is a specific characteristic or a feature of a few individuals of *M. pyramidalis*. The species are from the same formation.

Meekella pyramidalis (Newberry)

(Plate 43, figures 4-6)

1861 *Streptorhynchus pyramidalis*. Newberry, *Rept. upon Colo. River of the West exp. by Lieut. Ives*, pt. 3, p. 126, pl. 2, figs. 11-13.

Carboniferous (Kaibab) limestone over red cross-stratified sandstone, Camp 70, on high mesa west of Little Colorado.

Description. Shell medium-sized to large. Length about same as width. Ventral valve in small specimens has pyramidal shape due to high cardinal area; longitudinal surface slightly arched. In larger specimens arching of ventral valve becomes more prominent; pyramidal shape less so. The cardinal area curves posteriorly from a right angle to the plane of the shell margin. Its width is slightly less than that of the shell and about twice its own height. Delthyrium is approximately one-third to one-fourth the width of the cardinal area and has a sharply raised narrow median part. Delthyrial supporting plates are subparallel.

Dorsal valve reaches its maximum width at about mid length, and has a rounded anterior margin. In small specimens very slight convexity or none at all except at umbo, where curvature is marked. In large forms the curvature often becomes pronounced.

The surface of both valves is marked by 11 to 13 fairly regular and equal-sized coarse plications which in larger specimens become nodose and are crossed by conspicuous parallel growth lines near the anterior margins. The plications extend within 5-10 mm. of the beaks. Fine, distinct liræ, about 5 in the space of 1 mm., cover the shell parallel, in general, to the plications. Toward the anterior ends of large specimens they are seen to bifurcate and increase as the sulci become wider. They extend posteriorly to the beaks.

Measurements. Typical specimens (in millimeters):

Locality	Length, ventral valve	Length, dorsal valve	Width	Height, delthyrium	Length, hinge line
All specimens from	28	24	25	11	2
Fossil Mountain,	....	25	28	....	....
Grand Canyon	54	....	56	18	38
	....	49	57	....	27
	....	....	....	16	38

Discussion. In the Grand Canyon National Park collection there are four or more specimens of small size (see first two listed under measurements) which conform very closely to the type as described and figured by Newberry. Certain others which are much larger and more globose, hence less pyramidal in shape, were at first thought to represent another species. Careful consideration of the entire series, however, has convinced the writer that no constant differences such as should be represented in distinct species can be shown. Evidence strongly suggests that the larger forms are the adults of the smaller ones, since they occur together, in the same horizons and beds, and the posterior portions are seen to be essentially the same in every character which is constant. The loss of pyramidal shape and the globose form of the large specimens, therefore, is thought to be the natural outcome of growth. Furthermore, innumerable variations in shell shape appear to be explainable only by the fact that the species is one which is especially susceptible to the development of individual abnormalities and monstrosities, as well as to the effects of later shell distortion.

Comparison with other Kaibab species. From the Kaibab formation the only other species of this genus to be described thus far is *Meekella occidentalis* (Newberry). The original description states that this species resembles *M. pyramidalis* but has twice the horizontal diameter and is broader, flatter, and less strongly ribbed and striated. At another place Newberry refers to a broader area and narrower foramen in *M. pyramidalis*.

The writer has examined the type of *M. occidentalis* but has been unable to see that of *M. pyramidalis*. Based on this much information, he feels that the comparisons made by Newberry adequately bring out the differences shown in the specimens with which that palæontologist dealt. As has already been pointed out, however, the writer finds the original description of *M. pyramidalis* to be too limiting. In addition, since no other forms exactly comparable to the type of *M. occidentalis* have been found in the type locality, despite considerable searching, the validity of this species seems not at all convincing. The writer suspects the type specimen to be an abnormally flat *M. pyramidalis*. Judging from intermediate forms in the Grand Canyon collection this may easily be the case; however, at least until more material is available no change in status is proposed.

Comparison with other Permian species. Because of the rather fine distinctions made and the inadequate illustrations used by King, the writer has found extreme difficulty in comparing *M. pyramidalis* with the species from the Glass Mountain Permian studied by King. Since it has not been possible to examine his material, only a few general comments based on descriptions will be attempted. *M. globosa* King appears to resemble most closely the large forms of *M. pyramidalis*, and indeed differs only in greater number of plications from certain specimens of the latter, so far as can be ascertained from its description.

Meekella attenuata and especially *M. difficilis* described by Girty and found by King in the Leonard formation appear to resemble somewhat the small specimens of *M. pyramidalis*. Both seem to be consistently smaller, and to vary in numerous details, but the consistency of these features seems not to be well enough known to use in the present comparison.

Locality and horizon. Found in many parts of β member of the Kaibab formation. Specimens in Grand Canyon National Park collection represent localities as follows: Fossil Mountain, Bright Angel Point, and Bright Angel Trail in Grand Canyon; Marble Flats on the Kaibab Plateau; Hilltop at Havasu Canyon; Toroweap Valley; Clover Creek on Mogollon Plateau.

Other localities represented by specimens which have been referred to this species are the following (numbers in parentheses refer to references in bibliography): Aubrey Cliffs near Seligman (10); 3 miles south of Jacob's Lake (77); House Rock Valley (77); Parusi-Wompats Spring (62); Goodsprings Quadrangle, Nevada (32); Hurricane fault scarp, 18 miles south of Hurricane (73). With the possible exception of the Nevada material, all these came from the β member of the Kaibab formation.

Derbya nasuta Girty

(Plate 44, figures 1, 2)

1908 *Derbya nasuta*. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 182-183, pl. 26, figs. 6-6c.

"Delaware Mountain formation," Diablo Mountains (sta. 2764).

1930 *Derbya nasuta*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, pp. 59-60, pl. 8, figs. 1, 2.

Permian: Hess, Leonard, Word formations, Glass Mountains, Texas; Leonard formation, transition beds, Shafter; Hess formation, Bone Canyon member, Sierra Diablo; limestone of Pichagua, Las Delicias.

Description. Shell large with irregular growth. Width greater than length. Ventral valve rather high, slightly convex longitudinally. Cardinal area high, from obtuse angle with plane of the edge, has concave curvature longitudinally but flat surface transversely; width considerably less than maximum shell width, which is about mid length.

Dorsal valve strongly convex with umbo inflated. Shell outline expands rapidly below hinge line.

Surface of both valves covered with thin, closely spaced, radiating liræ which increase in number anteriorly by intercalation. These occur usually 12 or 13 to the space of 5 mm. Irregular, concentric growth lines often distort these toward the anterior margins.

Measurements. Typical specimens (in millimeters):

Specimen	Length, ventral	Length, dorsal	Width, maximum	Width, hinge line	Height, cardinal area	Del-tidium, base	Liræ per 5 mm.
Girty's type.....	75	....	90	50	25	11	Usually 10-11
Bright Angel Point.....	50	44	52	39	13	8	12
Fossil Mountain.....	54	....	62	....	....	....	13
Fossil Mountain.....	....	37	45	....	....	....	....

Comparisons. The fine, closely spaced liræ, the relatively narrow hinge line as compared with maximum shell width, and the large size of the shell are distinctive characteristics of this species and will readily serve to distinguish it from *Derbya regularis*, also of the Kaibab formation. *D. grandis* Waagen is said to be similar but differs "in having the hinge about as long as the greatest width of the shell and a narrower deltidium."

Locality and horizon. This species has been collected from several horizons and localities of the Kaibab formation, all in the upper part of the β member, facies 1 and 2. Specimens in the Grand Canyon collection represent the following localities: Fossil Mountain and Bright Angel Point, Grand Canyon. Specimens have been recorded by the writer from Hilltop, Toroweap Valley, and Clover Creek, Mogollon Plateau, in addition.

Specimens referred in published lists to this genus (or *Orthotetes*) and, in part at least, representing this species, are from the following localities (numbers in parentheses refer to bibliography): Rock Canyon, 15 miles south of Hurricane (73); Narrows, 2.5 miles west of Virgin City (73); 3 miles south of Jacob's Lake (77); Grand Wash Cliffs at Bronze-L mine (44); Parusi-Wompats Spring (62); Aubrey Cliffs near Seligman (10); Goodsprings Quadrangle, Nevada (32). The Nevada specimens may not be from the Kaibab β member, but all the others definitely are. Some of them may refer to *D. regularis*, however.

Derbya regularis McKee, n. sp.

(Plate 44, figures 3, 4)

Description. Shell medium to large, subsemicircular. Ventral valve rather flat with surface approximately a plane but showing concentric undulations of growth near margins of large specimens. Hinge line nearly equal or equal to maximum width. Beak pointed and slightly twisted. Cardinal area flat, wide, lying at about 130° to the plane of the margin. Deltidium strongly convex, moderately high.

Dorsal valve moderately convex, with weakly developed median sinus. Umbo inflated, beak small and incurved.

Surface marked with coarse, strongly elevated, and rounded liræ; between 5 and 7 to the space of 5 mm.; remarkably regular. New liræ are introduced by intercalation, starting with subnormal width but quickly attaining the average thickness anteriorly.

Measurements. Typical specimens (in millimeters):

Specimen	Length, ventral	Length, dorsal	Width, maximum	Width, hinge line	Height, cardinal area	Del- tidium, base	Liræ per 5 mm.
<i>Derbya</i> ? <i>crenulata</i> , Girty's type	19.5	18.5	30	30	5	2.5	6-7
<i>D.</i> ? <i>crenulata</i> , King's specimen . . . . .	....	27	39	35	....	....	7-8
<i>D. regularis</i> , Fossil Mountain . . . . .	....	....	48	48	9	9	6-7
<i>D. regularis</i> , Fossil Mountain	46	....	58	....	....	....	7

Comparisons. The specimens referred to this species are all considerably larger than those described by Girty as *Derbya* ? *crenulata* and apparently also differ from

it in having a weakly developed median sinus. They resemble it and differ from most other described Permian species in coarseness of the liræ (number to space of 5 mm.) and in the proportionate width of the cardinal area, which is usually equal to the maximum shell width.

The Phosphoria species named *Orthotetes sulcus* by C. Branson appears to resemble the present species closely in general size and shape. It also has a sinus on the dorsal valve, but one which is more prominent, and its dorsal valve is said to be concave rather than essentially flat. So far as can be determined from description, its liræ are more numerous for any given width.

Locality and horizon. Not uncommon in various parts of facies 1 of the β member, Kaibab formation. Specimens in Grand Canyon collection are from Fossil Mountain and Bright Angel Trail, Grand Canyon.

Specimens from 3 miles south of Jacob's Lake were referred by Shimer (77) to *D. ? crenulata*, a similar form. For other specimens of this genus recorded in published lists and probably partially referable to this species, see under *D. nasuta*.

Types. Cotypes, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-600, 601, 602, 603, 604.

***Chonetes kaibabensis* McKee, n. sp.**

(Plate 44, figures 5-12)

- 1877 *Chonetes granulifer*. White, U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 4, pp. 122-123, pl. 9, figs. 8a, b, c.
Carboniferous, upper Aubrey limestone, Kanab Canyon, Arizona.
- 1908 [?] *Chonetes* sp. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 229-230.
Delaware Mountain formation, basal black limestone, Guadalupe Point, Texas.
- 1930 [?] *Chonetes quadratus*. King [non Girty], *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 63, pl. 9, figs. 7-11.
Upper Word formation, Glass Mountains; Kaibab limestone of the Grand Canyon region.

Description. Shell medium-sized, usually definitely subquadrate in outline but occasionally subsemicircular. Ratio between length and width normally 0.60-0.65, somewhat less on young specimens. Hinge line regularly equals the greatest breadth of the shell, and the cardinal angle is 90° or close to it. Shell not mucronate, sides nearly or exactly parallel.

Ventral valve moderately or only slightly arched; beak small and depressed. Sinus absent or extremely inconspicuous and shallow, except where exfoliation has exposed the inner shell; here often a very thin, narrow, but definite sinus is seen. Lateral slopes between the umbo and the cardinal extremities are slightly concave.

The narrow cardinal area is widest toward the center and tapers toward the cardinal extremities. Weathered specimens show tubules passing through the areas, inclining inward posterior to the hinge line. These were doubtless originally joined to cardinal spines, which were about 16 in number.

Outer shell surface seems to be lirated but may be smooth. This point has not been definitely determined despite an abundance of material, since the interior of the valves is covered with little spinules in closely arranged rows and this inner layer when etched out often gives the appearance of a finely lirated shell. Furthermore, weathering has destroyed the true outer surface on a majority of specimens.

Concentric growth ridges and depressions are near the anterior margins of most specimens.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Ratio, length to width	Locality	Length	Width	Ratio, length to width
Fossil Mountain.....	13	20	0.65	Kanab Canyon— <i>Cont.</i> ..	13	21	0.62
	13	20	0.65		15	24	0.63
Hilltop.....	12	19	0.63		12	19	0.63
	13	19	0.68		12	20	0.60
	12	19	0.63		13	20	0.65
Kanab Canyon	17	25	0.68		11	18	0.61
	13	20	0.65		12	20	0.60
	15	23	0.65		15	22	0.68
	15	22	0.68	Virgin City.....	11	18	0.61

Discussion. This species is distinguished by its strongly quadrate outline, low convexity, numerous cardinal spines, and lack of well-defined sinus. The older shells show a tendency toward greater convexity, more quadrate outline, and the development of larger pores along frontal margin (internal molds).

It is probable that the form described by King (non Girty) as *Chonetes quadratus* should be referred to this species, since his holotype comes from a locality in the Kaibab formation where *C. kaibabensis* is known to be common and his figures, as well as can be determined, correspond to the specimens at hand. Even though this form should prove to be different, the fact that his name was preoccupied precludes the possibility of confusion in nomenclature. His description does not exactly fit the specimens at hand in two respects, i. e. only 6 spines on each side of beak, and shallow sinus. Since the former is given only as an approximation and the latter might be due to exfoliation exposing the sinus of the inner shell or to specimens with extreme development in this direction, the differences do not appear to have great significance, especially in view of the great similarity in size, shape, and surface character.

The specimens from the Guadalupe Mountains described as *Chonetes* sp. by Girty probably also should be referred to *C. kaibabensis* since they apparently agree in such diagnostic characteristics as ratio of width to length, general size, lack of sinus, slight convexity, rows of internal spinules, and many cardinal spines.

Comparisons. Of the American Permian Chonetidæ, *C. ostiolatus* of the Phosphoria probably most closely resembles *C. kaibabensis* and is of about the same size. It differs primarily in having large pores scattered over the shell surface, and probably also in a higher convexity.

Another Permian species having the subquadrate outline is *C. platynotus* White, described from the "Carboniferous" of Utah and New Mexico. This small form apparently differs in having fewer cardinal spines, a shallow sinus, and a higher ratio of length to width.

In the Pennsylvanian of Kansas and Nebraska some subquadrate forms occur, but they should be readily distinguished from *C. kaibabensis* by several characteristics. *C. granulifer* Owen has a shallow sinus and is mucronate. *C. geinitzianus* (Waagen) is a small form with fewer cardinal spines, shallow sinus, and mucronate character. See the accompanying table.

COMPARISON OF *Chonetes kaibabensis* AND RELATED SPECIES

Species	Surface	Sinus	Outline	Mucro- nate or winged	Cardinal angle	Cardinal spines	Length (mm.)	Width (mm.)	Ratio, length to width	Age and locality
<i>C. kaibabensis</i> McKee.....	Lirated(?)	None or slight	Subquadrate	None	90°	14-16	11-15	18-24	0.60-0.68	Permian, Ariz.
<i>C. geinitzianus</i> Waagen.....	Smooth	Shallow	Subquadrate	Definite	90°	10-12	7.5	12	0.62	Pennsylvanian, Kans., Nebr.
<i>C. ostialatus</i> Girty.....	Pores	None	Subquadrate	Little	90°	10-12	18	31	0.58	Permian, Wyo., Ida., Tex.
<i>C. platynotus</i> White.....	Fine liræ	Shallow	Subquadrate	Little	80°	10-12	9	12	0.75	Carboniferous, Utah, N. M.
<i>C. granulifer</i> Owen.....	Fine liræ	None to shallow	Subquadrate	Definite	70-80°	14-16	10-14	18-25	0.56	Pennsylvanian, Kans., Nebr.
<i>C. granulifer</i> var. <i>armatus</i> Girty.....	Fine liræ	Shallow	Subquadrate	Definite	70-80°	12-14	9-11	13-15	0.69-0.73	Pennsylvanian, Kans., Nebr.

Comparison with Eurasian and South American forms. *Chonetes ambiensis* (Waagen) of the Salt Range is similar to *C. kaibabensis* of the Kaibab formation in most respects but is not subquadrate and differs decidedly in having a high ventral cardinal area which forms a marked angle between the cardinal margins. *C. polita* McCoy of northern Europe is also similar but is much smaller, has a very gibbous ventral valve, and does not have a subquadrate outline. In type of outline, smooth shell surface, and lack of sinus, *C. kaibabensis* closely resembles *C. cf. geinitzianus* Reed of Yunnan and *C. amazonicus* Derby of Brazil. The former is not well enough known for a close comparison. The latter is somewhat smaller but apparently very similar in other respects. *C. obtusa* Schellwin has a shallow sinus which should serve to distinguish it.

Locality and horizon. Very common in the β member of the Kaibab formation. Appears earlier and extends eastward farther in this limestone than does any other brachiopod except *Productus bassi*. Found at Yaki, Bright Angel, and Hermit Trails and at Fossil Mountain in Grand Canyon. Common at Hilltop near Havasu Canyon, at Kanab Canyon, Aubrey Cliffs near Seligman, Toroweap Valley, Badger Canyon near Lees Ferry, and in the Narrows of the Virgin River. In the southern part of the region near Pivot and Clover Creeks on the Mogollon Plateau and at Sycamore Canyon, it is also abundant in some of the lowest horizons of the member.

Types. Cotypes, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620.

Chonetes sp.

(Plate 44, figure 13)

Description. Shell strongly transverse, short and wide, cardinal angle relatively small. Greatest width at hinge line.

Ventral valve slightly arched; sinus weak. Cardinal spines, 8 or more on each side of beak.

Outer surface covered with fine radiating liræ. When exfoliated, as in most specimens, inner surface shows rows of rounded pits, especially prominent near the anterior margin.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Ratio, length to width	Locality	Length	Width	Ratio, length to width
Grand Canyon village...	7	14	0.50	Beaver Dam Moun-			
Fossil Mountain.....	7	14	0.50	tains— <i>Continued</i>	9	16	0.56
St. George.....	8	14	0.57		9	16	0.56
	7	12	0.58	Meteor Crater.....	8	15	0.53
Beaver Dam Moun-					8	16	0.50
tains.....	7	13	0.53		9	17	0.53
	7	14	0.50		6	10	0.60

Discussion. This species is distinctive because of its low ratio of length to width and its small cardinal angle, causing sharply converging sides. Although it apparently represents an undescribed species, the writer does not propose to name it at this time, since nearly all the material on hand represents internal molds and would not be satisfactory for types.

Comparisons. *Chonetes granulifer* var. *transversalis* Dunbar and Condra appears to be very similar to the form here discussed. It likewise has a hinge line much extended into mucronate cardinal extremities and has 8 to 10 cardinal spines on each side. Its average size is somewhat greater and it occurs in the Pennsylvanian.

Distribution. Not uncommon in certain of the thin-bedded magnesian limestones of α member, Kaibab formation. Specimens examined were from: Padre Canyon, 2 specimens; Meteor Crater, 4 specimens; Grand Canyon village, 2 specimens; 4 miles south of St. George, 2 specimens. Present locally in β member, Kaibab formation. Specimens examined from Beaver Dam Mountains (possibly α member), 4; Fossil Mountain, 1.

Chonetes (Lissochonetes) subliratus Girty

(Plate 44, figures 14-17)

1861 *Chonetes verneuilliana*. Newberry, *Rept. upon Colo. River of the West exp. by Lieut. Ives*, pt. 3, p. 128.

Cherty limestone, on banks of the Colorado, 100 miles northwest of the San Francisco mountain.

"Outline of shell more oblong, mesial sinus less deep, carinations bordering it less conspicuous, lateral sinuses not generally visible, tubes of cardinal border varying from 3 to 5 on each side of beak, beak scarcely projecting beyond cardinal border, etc." In other respects similar.

1908 *Chonetes subliratus*. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 228-229, pl. 20, figs. 4-7.

Dark limestone, Pine Spring; Delaware Mountain formation, Guadalupe Point; ? basal Capitan, hill southwest of Guadalupe Point.

1930 *Chonetes subliratus*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, pp. 63-64, pl. 9, fig. 25, pl. 10, figs. 1-7.

Hess (?) formation, Glass Mountains; Leonard formation, Glass Mountains, extremely abundant; Word formation, Glass Mountains; Vidrio member, Glass Mountains; lower Hess formation, Sierra Diablo; Hess formation, Sierra Diablo; Bone Canyon member, Sierra Diablo; Victoria Peak member, Sierra Diablo; Leonard formation, Finlay Mountains.

Description. Shell of medium size, prominently mucronate or winged, and distended. The lateral margins tend to converge from the ears anteriorly, with, however, a gentle outward bulging whose maximum extension is about midway. Six or seven (probably seven) cardinal spines are on each side of the beak. Sinus is deep and wide. On each side of it is a prominent plication, one diverging from the other toward the anterior with an angle of about 50° , and each sloping with rapid descent toward the wings, which are depressed and convex. The dorsal valve conforms closely to the marked curvature of the ventral.

Cardinal areas are narrow and taper uniformly toward cardinal extremities in both dorsal and ventral valves. The ventral cardinal area is distinctly wider than the dorsal.

Surface of shell is essentially smooth, with no trace of radial striation. Weathered specimens give the appearance of radiating markings because of pustules of internal structure, which are arranged in rows.

The internal structure of the dorsal valve consists of small crural plates which

bound the sockets and are at about 30° to the hinge line. Just before the cardinal process is a small pit and in front of this three ridges diverge. The center one or septum extends about three-quarters of the shell length and is club-shaped. The other two ridges end in needle-like processes and extend only about 2 mm. They form an angle of about 20° with the septum.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Ratio, length to width	Locality	Length	Width	Ratio, length to width
Hermit Trail.....	12	18	0.66	Fossil Mountain.....	9	13	0.69
	12	18	0.66		11	16	0.68
Fossil Mountain.....	11	17	0.64		8	12	0.62
	12	17	0.70		9	13	0.69
Hilltop.....	11	18	0.61	Kanab Canyon.....	12	18	0.66
	12	20	0.60		11	18	0.61
Kanab Canyon.....	12	18	0.66		8	13	0.61
	8	13	0.61		9	14	0.64

Discussion. Unusually great thickness for this genus, due to strong arching of the ventral valve, is a conspicuous feature. Also, proportions seem to be remarkably constant although the young specimens are relatively wider than are the mature. The young also have ears, but differ in being slightly lirate.

Comparisons. As indicated in the accompanying table, the forms from the Kaibab formation agree with *Chonetes subliratus* Girty of the Guadalupe Mountains in every detail. In the original description Girty states that this species has "moderately fine ribs," which is not true of the Grand Canyon forms. His plates fail to illustrate this feature, however, and as King points out, "it is doubtful if Girty had perfect specimens on which to base his species."¹

Of the seven smooth-surfaced forms of *Chonetes* which are more or less similar to *C. subliratus*, all may be differentiated by one or more of the diagnostic characters given in the accompanying table.

Chonetes quadratus Girty has lateral margins which are nearly parallel instead of converging anteriorly, and it has no ears.

Chonetes ostiolatus Girty differs in having a very shallow sinus, in having a ventral valve only slightly convex, and in being much larger.

Chonetes hillanus Girty has a narrower sinus, less divergence of the humps anteriorly, more cardinal spines, and lower ratio of length to width.

Chonetes consanguineus Girty has a narrower sinus with less diverging humps on each side.

Chonetes geinitzianus var. *geronticus* Dunbar and Condra and var. *plattsmouthensis* Dunbar and Condra are considerably smaller and have less converging (more parallel) lateral margins.

Chonetes verneuillianus Norwood and Pratten is greatly different in that it has definite liræ. Also it has nearly parallel lateral margins.

Locality and horizon. Abundant in upper part of β member in many localities of facies 1, Kaibab formation. Specimens in Grand Canyon collection are from Bright Angel and Hermit Trails and Fossil Mountain in Grand Canyon, and from

¹ R. E. King, Univ. Texas Bull. 3042, pt. 2, p. 64, 1930.

COMPARISONS OF *Chonetes subliratus* AND RELATED SPECIES

Species *	Surface markings	Divergence of humps †	Sinus	Lateral margins	Presence of ears	Cardinal spines	Average length (mm.)	Average width (mm.)	Ratio, width to length
<i>C. subliratus</i> Girty, Kaibab formation.....	Smooth	50°	Deep	Diverging	Present	14	12-20	9-12	0.60-0.70
<i>C. subliratus</i> Girty.....	Smooth	50°	Deep	Diverging	Present	14	14-26	10-15	0.51-0.71
<i>C. quadratus</i> Girty.....	Smooth	55°	Deep	Parallel	Absent	....	11	Small	....
<i>C. geinitzianus</i> var. <i>plattsmouthensis</i> Dunbar & Condra.....	Smooth	50°	Medium	Nearly parallel	Prominent	10?	12	7.5	0.62
<i>C. geinitzianus</i> var. <i>geronticus</i> Dunbar & Condra	Smooth	40°	Deep	Nearly parallel	Prominent	10	11	6	0.55
<i>C. verneuillianus</i> Norwood & Pratten.....	Liræ	35°	Deep	Moderate divergence	Prominent	8-10	10-16	7-10	0.62-0.64
<i>C. ostiolatus</i> Girty.....	Liræ	30°	Shallow	Diverging	Absent	....	31	18	0.58
<i>C. hillanus</i> Girty.....	Liræ	30°	Medium	Diverging	Absent	18	22	10	0.45
<i>C. consanguineus</i> Girty.....	Liræ	30°	Medium	Diverging	Absent or small	10-12	Medium	Medium	....

* According to the classification of the Chonetidae of Dunbar and Condra, 1932, the first five belong to the group *Lissochonetes* (smooth, wide sinus), *Chonetes verneuillianus* with striations and narrow sinus to *Chonetina*, and the last three to a position between these two, with a smooth surface as in *Lissochonetes* but a narrow sinus as in *Chonetina*.

† "Humps" refers to folds bordering median sinus.

Hilltop at Havasu Canyon. There are 24 specimens in the U. S. Geological Survey collection from Kanab Canyon. Also, this species has been recorded by the writer from Aubrey Cliffs near Seligman and from Clover Creek on the Mogollon Plateau.

In published faunal lists specimens of *Chonetes* from the Kaibab formation have for the most part been listed as *C. hillanus*. King² suggests that these probably should be referred to his *C. quadratus* (= *C. kaibabensis*), but it seems more logical to the writer that reference should be to the latter species since *C. hillanus* is closely related to *C. subliratus*. The following records have been listed (numbers in parentheses refer to bibliography): *C. hillanus*, Kaibab α and β members, northwestern Arizona and southeastern Utah (73); *C. hillanus*?, Kaibab β member, Circle Cliffs, two localities (27).

Productus (Dictyoclostus) bassi McKee, n. sp.

(Plate 45, figures 1, 2)

- 1861 *Productus semireticulatus*. Newberry, *Rept. upon Colo. River of the West exp. by Lieut. Ives*, p. 124.
Cherty limestone, near the junction of the Great and Little Colorado.
- 1877 *Productus semireticulatus* [in part]. White, U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 4, pp. 111-113, pl. 8, figs. 1a, b, c.
Carboniferous: near Bill Williams Mountain; Tenney's Ranch, Kaibab Plateau; head of Dry Fork and Kanab Canyon (Aubrey limestone), Arizona; etc.
- 1877 *Productus ivesii*? Hall and Whitfield, *Rept. U. S. Geol. Exploration of the Fortieth Parallel, Paleontology*, vol. 4, pt. 2, pp. 67-68, pl. 7, figs. 6, 6a, 6b.
Fossil Hill, White Pine Mountains; Railroad Canyon, Diamond Mountains; west of San Francisco Mountain; etc.
- 1909 *Productus ivesi*. Girty, *The Manzano group*, U. S. Geol. Surv. Bull. 389, p. 65.
San Andres limestone, Nogal Creek, Mesa del Yeso, and San Andres, Yeso formation, Mesa del Yeso.
- 1930 *Productus ivesi*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, pp. 69-71, pl. 12, figs. 1-6.
Hess formation, Glass Mountains; Leonard formation, Glass Mountains, common and well preserved; Word formation (?), Glass Mountains; Hess formation, Sierra Diablo; Bone Canyon member, Sierra Diablo; Victorio Peak member, Sierra Diablo; Victorio Peak member, Brackett Draw; Leonard formation, Shafter; Leonard formation, Finlay Mountains; Gym formation, Wylie Mountains; limestone of Puertacitas at Puertacitas.

Description. Shell large and proportionately long. Ears prominent, strongly arched, and extended. Ventral valve very convex especially in the posterior part but somewhat flatter anteriorly; entire curvature of valve approximately 180°. Marked arching toward posterior margin terminates in beak which extends beyond hinge line. In front of area of greatest curvature a shallow to moderately well-developed sinus appears and extends to the front. Lateral margins drop off abruptly, giving the visceral disk a quadrate outline. Dorsal valve only slightly concave, sometimes nearly flat except near the anterior margin, where there is an abrupt but slight outward curvature.

Surface characterized by moderately coarse costæ separated by sulci of about equal width. Occasionally a costa splits into two or combines with another to

² *Ibid.*, p. 63.

form one, but in general they are constant. The ventral valve has concentric rugæ which cross the costæ in the posterior part, thus giving rise to nodes, some of which are the bases of large hollow spines. These hollow spine bases, about 0.75 mm. across, occur nearly all over but are especially numerous along the hinge and on the ears. From the ears groups of long spines are often seen extending laterally. On the dorsal valve concentric rugæ also cross the costæ but extend somewhat farther forward and the intersection places are marked by pits instead of spines.

The interior of the ventral valve is marked by deep diductor muscle scars which taper posteriorly from a maximum width beyond the mid length of the shell, and by multilobate adductor scars located on the raised platform between these and separated by a low ridge. The interior of the dorsal valve has a narrow elevated septum extending between the muscle scars. From it brachial ridges extend laterally on each side and finally curve forward to form large brachial loops, the open ends of which are connected by faint ridges with the septum again. The cardinal process is large and trifid with the middle branch divided by a groove. It extends beyond the hinge line but from it at that place two ridges extend laterally.

Measurements. Typical specimens (in millimeters):

Locality	Length, straight	Length, along curve	Width	Thick- ness	Locality	Length, straight	Length, along curve	Width	Thick- ness
Shinumo Can- yon.....	67	142	78	35	Kanab Canyon				
	70	122	76	32	—Continued.	57	101	70	37
	66	131	72	36	Narrows.....	55	96	55	26
	70	136	85	40		47	78	52	25
Kanab Canyon	65	157	76	43	Hurricane....	53	156	85	34
	65	101	70	32		56	118	72	38

Discussion. In his report of 1861 Newberry referred a species of *Productus* from the cherty limestone near the junction of the Colorado and Little Colorado Rivers to *P. semireticulatus* Martin. A somewhat similar species from "the banks of the Colorado near the mouth of Diamond River" he described and named *P. ivesi*. The species which is here described and named *P. bassi* (after Bass Camp, where it is especially abundant) is a large, long form which is very similar to the English *P. semireticulatus*. It undoubtedly is the one which Newberry referred to that species, since it occurs throughout the cherty limestone in the locality which he gave and it answers his description of being exceptionally large. Girty in describing the Manzano fauna of New Mexico and King in the Glass Mountain fauna of Texas encountered what was obviously this same species, but they referred it to *P. ivesi*. Both Newberry's description and his figures, however, show that that reference was incorrect and that true *P. ivesi* is the far shorter and proportionately broader form which occurs below the cherty limestone in the underlying Toroweap formation.

The writer has examined large series of specimens of both *P. bassi* and *P. ivesi* in the collections of the U. S. Geological Survey, the Grand Canyon National Park, the University of Arizona, and elsewhere, and has found that although the species are similar in many respects and undoubtedly closely related, certain consistent differences are apparent. These are brought out in the following tabular comparison:

<i>Productus ivesi</i>		<i>Productus bassi</i>	
Costæ relatively parallel near beak		Costæ diverge strongly near beak	
General shape of shell square		General shape of shell oblong	
Side profile rounded		Side profile elongated	
Dorsal valve strongly concave, fold develops early		Dorsal valve nearly flat, geniculated near front, fold develops late	

The shorter and proportionately broader *P. ivesi* occurs alone in the limestone of the Toroweap formation. The type specimen undoubtedly came from this limestone judging from the locality given and the character of fossil preservation. Whether it also occurs with *P. bassi* above has not been determined with certainty, but it is thought not. Young and poorly developed specimens of the latter naturally have a resemblance to *P. ivesi*, but there should be no question in the case of well-preserved mature specimens.

Certain productids collected by Hall and Whitfield from Nevada in 1877 were figured by them under the name of *P. ivesii*? and briefly discussed. They questioned the identity, rightly as it now appears, because they held that their specimens were more produced anteriorly and narrower in the umbonal region, and contained a bifid, not single, ridge in the dorsal valve. Their figure and description indicate that the Nevada specimens were almost surely of the species here named *P. bassi*.

Comparisons. The type *P. semireticulatus* Martin from Great Britain as re-defined by Muir-Wood in 1928 is remarkably similar to *P. bassi*, a fact which is very apparent from her excellent figures. In size and proportions these are practically identical. The costæ of *P. bassi* are possibly a little wider and the sinus more pronounced, though the validity of these criteria is questionable. The principal distinguishing characteristics appear to be the more numerous spine bases scattered over the venter as well as the other slopes of *P. bassi* and the more extensive reticulation of *P. semireticulatus*. Muir-Wood states that elongated nodular swellings occur at the intersections of ribs and costæ, on the venter, and especially on the cardinal slopes in the English species. It is not known whether or not the numerous narrow spines 1.5 to 2 inches long, which extend out from the ears of *P. bassi*, occur on *P. semireticulatus*. *P. pinguis* Muir-Wood somewhat resembles both *P. semireticulatus* and *P. bassi* but may be readily distinguished from both by its more rounded venter, more convex flanks, more prominent costæ, and better-defined ribs, and by three rows of large spine bases on its flanks.

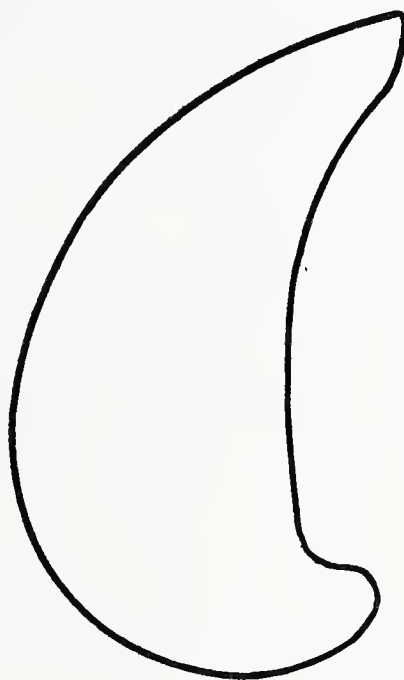
The American members of the Productidæ which have been designated by various authors as *semireticulatus* are generally recognized as being different from the British type and indeed probably represent a number of distinct forms. Many of them have been redescribed as new species. Detailed descriptions have, in general, been omitted in references to this species in American faunas, but an examination of figures given by Hall, Meek, Hall and Whitfield, Winchell, Weller, Keyes, Morningstar, and Thomas, and of specimens from the Middle Western states, has shown convincingly that the forms referred to are considerably smaller and proportionately



P. pinguis Muir-Wood
(After Muir-Wood)



P. bassi McKee



P. semireticulatus Martin
(After Muir-Wood)

wider than either *P. bassi* or the type *P. semireticulatus*. Furthermore, they differ from *P. bassi* by having finer, less parallel costæ with fewer spines, a more subtriangular visceral disk, and less abrupt and steep lateral margins. Other details of difference might be enumerated, but enough have been pointed out to indicate the distinct forms represented by these shells.

In large size and similar shape of the visceral area, *P. spiralis* Waagen of the Salt Range, India, is comparable. It may be readily distinguished by its far larger costæ and by the relative scarcity of spines.

Productus inca d'Orb and *P. leei* Girty, considered by King to be synonymous, not only are much smaller than *P. bassi* but also have fewer spines, lower beaks, more prominently reticulated posterior parts, and subtriangular rather than subquadrate visceral disks.

Locality and horizon. This is by far the most common species of brachiopod in the Kaibab formation and is represented in a greater range of horizons than is any other form. Abundant throughout facies 1 and 2 of the β member from southern Nevada to eastern Grand Canyon. Present in parts of facies 4 but absent in facies 3 and 5. Present but not common in α member of Kaibab, facies 1 (?), 2, 3 (?), 4, but not 5.

Types. Cotypes, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-630, 631, 632, 633, 634, 635.

Productus (Dictyoclostus) ivesi Newberry

(Plate 45, figures 3-7)

- 1858 [?] *Productus semi-reticulatus* [in part]. Marcou, *Geology of North America*, p. 46, pl. 5, figs. 4, 4a, pl. 6, fig. 6.
Carboniferous.
- 1861 *Productus ivesi*. Newberry, *Rept. upon Colo. River of the West exp. by Lieut. Ives*, pt. 3, p. 122, pl. 2, figs. 1-8.
Middle Carboniferous limestone, banks of the Colorado near mouth of Diamond River.
- 1909 Not *Productus ivesi*. Girty, *The Manzano group*, U. S. Geol. Surv. Bull. 389, p. 56.
- 1930 Not *Productus ivesi*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, pp. 69-71, pl. 12, figs. 1-6.

Description. Newberry's original description of this species, the type of which he collected on the rim of Grand Canyon near Diamond Creek in 1857, is as follows: "Shell large, transverse; width $\frac{1}{4}$ greater than extreme length, strongly revolute; beaks projecting beyond the cardinal border. Ventral valve: Sinus strongly marked, extending from near the beak to the anterior border; ears broadly expanded, lateral angles acute; visceral region somewhat reticulated and tuberculated; anterior surface striated; striæ coarse, nearly uniform, and crowned with tubercles; ears covered with rows of tubular spines radiating in different directions, of which those on the cardinal border exceed two inches in length. Dorsal valve: Strongly concave, surface thickly set with spines scarcely exhibiting a determinate arrangement. Interior: Cardinal tooth ob-conical, narrow, trifid; from it a distinct but slightly elevated median ridge extends to the center of the dorsal valve; hepatic impressions somewhat elongated; impressions of the adductor muscles semicircular, with nearly uniform outline; interior of ventral valve marked with a strong ridge

corresponding with the external sinus, of which the surface is striated; muscular impressions quadrate, deep."

The preceding description seems to the writer to be entirely adequate and nothing need be added here. Newberry specifically states that the shell is proportionately wide and his figures ably illustrate these proportions, which serve to distinguish this species from the somewhat similar but larger and longer form *Productus bassi*, found so abundantly in the Kaibab formation. The strong concavity of the dorsal valve should also be emphasized as a good diagnostic feature.

Measurements. Typical specimens (in millimeters):

Locality	Length, straight	Length, along curve	Width	Thickness	Locality	Length, straight	Length, along curve	Width	Thickness
Diamond Creek, Newberry's type.....	33 +	54	45	16	Grand Wash...	51	82	54	23
Toquerville, Utah.....	45	79	45	24		45	84	50	20
	46	77	47	22	Narrows.....	36	60	33	16
	45	75	48	21		41	68	42	21
						40	79	42	21

Locality and horizon. Found abundantly in facies 1 and occasionally in facies 2 of the β member, Toroweap formation. Specimens have been collected from Yaki Trail in Grand Canyon, Hilltop at Havasu Canyon, Toroweap Valley, Grand Wash Cliffs, Hurricane Cliffs, Shivwits Plateau, and many other localities in northwestern Arizona and southwestern Utah.

Productus (Dictyoclostus) occidentalis Newberry

(Plate 46, figures 1-4)

- 1858 [?] *Productus costatus*. Marcou, *Geology of North America*, p. 46, pl. 5, fig. 5. Carboniferous: Cedar Creek, Mogollon Mountains, tributary of Gila River, sources of Colorado Chiquito.
- 1861 *Productus occidentalis*. Newberry, *Rept. upon Colo. River of the West exp. by Lieut. Ives*, pt. 3, p. 122, pl. 2, figs. 9-10. Cherty limestone near top of Carboniferous, banks of Cascade River near junction of Great and Little Colorado.
- 1861 [?] *Productus costatus* [in part]. Newberry, *Rept. upon Colo. River of the West exp. by Lieut. Ives*, pt. 3, p. 123. Upper Carboniferous, cherty limestone, on banks of the Colorado.
- 1877 [?] *Productus costatus* [in part]. White, U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 4, pp. 109-111, pl. 8, figs. 2a, b, c, d. Carboniferous: Kanab Canyon, Arizona; south of St. George, Utah; etc.
- 1908 *Productus occidentalis*. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 262-263, pl. 12, figs. 4-4c. Middle Capitan, Capitan Peak; dark limestone, Pine Spring.
- 1930 *Productus occidentalis*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, pp. 72-73, pl. 14, figs. 10-14. Leonard formation, Glass Mountains, abundant; Word formation, Glass Mountains; Bone Canyon member, Delaware Mountains; Victorio Peak member, Brackett Draw; Gym formation, Diablo Plateau.

Description. Shell medium-sized, highly arched and revolute, proportionately narrow. Hinge line forms the greatest width.

Ventral valve much inflated in umbonal region with curvature decreasing toward anterior margin. Ears moderately large, flattened, and set off from visceral area by distinct sinuses. Median sinus prominent, originating near beak and extending to anterior margin.

Dorsal valve concave in the visceral region and strongly geniculated at the outer border of that region.

Surface of both valves marked with large, coarse costæ, usually even but sometimes very uneven, nodose, and bifurcating; average number of costæ about 20; sulci rather wide. In the ventral valve the costæ are approximately parallel, but in the dorsal those on the anterior lateral margins converge to meet the parallel ones of the fold in the posterior region, thus displaying a very different pattern. Wrinkles of posterior part are faint or lacking; spines not very numerous.

Details of the internal structure have been described by King and need not be repeated here.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thick- ness	Locality	Length	Width	Thick- ness
Kanab Canyon	31	40	19	Shinumo Canyon— <i>Continued</i>	21	36	13
	32	48	20		19	32	10
	25	34	14		20	34	11
	27	38	15	3.5 mi. S. of St. George	15	28	8
	28	48	18		17	28	11
Shinumo Canyon	29	46	16		28	34	15
	36	52	22				

Discussion. The best diagnostic features of this species seem to be the coarse costæ, the approximate parallelism of the costæ in the ventral valve and their peculiar pattern in the dorsal, the distinctly narrow quadrate visceral area, the high arching of the ventral valve, and the incurved beak.

In the early stages of this study the writer was led to the belief that *Productus occidentalis* of Newberry was different from *P. occidentalis* of Girty and of King. This was due to Newberry's description, which does not fit a ventral valve of this species. This conclusion was reported by Stoyanow;³ the name *Dictyoclostus meridionalis* was proposed for the form as described by Girty and King. The writer has since had opportunity to examine Newberry's type specimen, which was a dorsal valve, and is convinced of his error. Thus, the name *D. meridionalis* is not to be applied.

The American forms most nearly similar to *P. occidentalis* are some of those referred to *P. costatus* Sowerby. Judging by the figures and localities given by Marcou for his "*P. costatus*," it was identical. The forms referred by Newberry and by White from the Colorado Plateau area probably also were *P. occidentalis*. Newberry specifically stated that his specimens were narrower and had less expanded wings and broader costæ than *P. costatus*, thus emphasizing three diagnostic features of *P. occidentalis*.

³ A. A. Stoyanow, *Correlation of Arizona Paleozoic formations*, Bull. Geol. Soc. Amer., vol. 47, p. 528, 1936.

Comparisons. *Productus costatus* of the Mississippi Valley and also *P. magnicostata* may be distinguished from *P. occidentalis* by weaker costation, more numerous spines, and a visceral area which is wider and less quadrate.

Typical *P. costatus* of Sowerby, occurring commonly in England, and somewhat similar forms from Russia, are proportionately much wider, show more reticulation posteriorly, and possess on each side a strongly developed radial costa bearing a row of large spines which separate the wings from the body of the shell.

In the Salt Range of India are several productids with coarse costæ, including *P. indicus*, which is also recorded by King from the Glass Mountains, Texas, but all these may be readily distinguished from *P. occidentalis* by their much larger size (except *P. subcostatus*), greater breadth, more prominent reticulation posteriorly, and various other characters.

Productus grandicostatus Chao, based on one specimen, appears to be very similar to *P. occidentalis*, judging from the figures and description, but it is not possible at this time to determine the exact relationship between these forms.

Locality and horizon. Kaibab formation, β member; very common west of Bright Angel Trail, along Hermit Trail, and at Fossil Mountain in Grand Canyon; common at Hilltop, Havasu Canyon. Found on Mogollon Plateau between Clover and Pivot Canyons. Specimens in U. S. Geological Survey collection which have been examined by the writer are from: Kanab Canyon, 5 specimens; 3.5 miles south of St. George, 3 specimens; Shinumo Canyon, 5 specimens.

Specimens referred to this species have been given in published lists from the following localities (numbers in parentheses refer to bibliography): Parusi-Wompats Spring (62); Goodsprings Quadrangle, Nevada (32); Aubrey Cliffs near Seligman (10); Grand Wash Cliffs at Bronze-L mine (44); mouth of Grand Wash and Horse Springs (44); House Rock Valley; 3 miles south of Jacob's Lake; Toroweap Valley; Hurricane fault scarp (77). With the possible exception of the Nevada specimens, all are from the β member, Kaibab formation.

***Productus (Dictyoclostus) paraindicus* McKee, n. sp.**

(Plate 46, figure 5)

1930 *Productus indicus*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 72, pl. 13, figs. 6-9.

Leonard formation, Glass Mountains; Word formation, Glass Mountains, abundant; upper Hess formation, Sierra Diablo; Leonard formation, Shafter; Word formation, thin-bedded zone, Shafter.

Description. Shell medium-sized, proportionately long, revolute with beak curved well over hinge line. Wings large, prominent, and arched. Hinge line straight, forming maximum width of shell.

Ventral valve with marked convexity forming a rather uniform curve in profile. Median sinus broad, moderately deep, uniform, beginning not far from the beak.

Dorsal valve not known from Kaibab formation.

Surface of shell marked by very unequal, large costæ which remain nearly parallel throughout length. Strength of costæ extremely variable in specimens. Heavy spines appear upon the posterior slope of the ears and scattered over the shell on the costæ.

Measurements. Specimens (in millimeters):

Locality	Length	Width	Thickness
Fossil Mountain.....	40 35	42 48	20 18

Discussion. This form, represented from the Kaibab formation by several ventral valves, seems to be identical with that described and figured from the Glass Mountains, Texas, by King and referred by him to *Productus indicus* Waagen. The similarity of this species to Waagen's Salt Range species is very marked, but the American form is so much smaller and narrower than the Indian one that the writer does not feel justified in considering them the same.⁴

Comparisons. The species bears a great resemblance to the much smaller *P. occidentalis*, but in addition to the difference in size is somewhat wider proportionately and has far more prominent ears.

Productus paraindicus differs, as does the Salt Range species *P. indicus*, from *P. subcostatus* by more irregular costæ and by the absence of a very prominent rib which separates the wings from the remainder of the shell.

Locality and horizon. Kaibab formation, β member; Fossil Mountain in Grand Canyon, Hilltop near Havasu Canyon.

Types. Cotypes, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-640, 641, 642, 643.

Waagenoconcha montpelierensis (Girty)

(Plate 46, figures 6-8)

- 1910 *Productus montpelierensis*. Girty, *Fauna of the Park City formation*, U. S. Geol. Surv. Bull. 436, p. 30, pl. 2, figs. 5-6.
- 1927 *Productus montpelierensis*. Girty, in *Geography, geology, and mineral resources of part of southeastern Idaho*, U. S. Geol. Surv. Prof. Paper 152, p. 80, pl. 28, figs. 12, 13.
- 1930 *Pustula montpelierensis*. C. Branson, *Paleontology and stratigraphy of the Phosphoria formation*, Univ. Missouri Studies, vol. 5, no. 2, p. 32, pl. 7, figs. 15-17. *Pustula* member, Wind River Mountains, Wyoming; phosphate beds, Montpelier, Idaho.
- 1930 *Waagenoconcha montpelierensis*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 81, pl. 19, figs. 5, 6.
Wolfeamp formation, *Uddenites* zone, Glass Mountains; Leonard formation, Glass Mountains; Word formation, Glass Mountains; Victorio Peak member, Sierra Diablo; limestone of Cerro Caballo, Las Delicias.

Description. Shell medium-sized, transverse, subcircular. Hinge line shorter than greatest width; cardinal angles rounded.

Ventral valve regularly convex in profile. Beak small, rapidly expanding, and strongly incurved. Visceral area triangular with steep slopes. Sinus narrow but prominent, beginning a short distance in front of the beak.

Dorsal valve almost flat but with slight depressions in front of and parallel to the hinge line and also on each side of a slight median fold. Ears small and depressed.

⁴ The incorrectness of correlating this species with *P. indicus* has previously been pointed out by A. A. Stoyanow in *Correlation of Arizona Paleozoic formations*, Bull. Geol. Soc. Amer., vol. 47, p. 531, 1936.

Surface of both valves marked with great numbers of small spine bases arranged in the quincunx pattern which is typical of the genus. Irregular, concentric wrinkles also occur toward the anterior portion but are not very prominent.

Internal characters not determined.

Measurements. Typical specimens (in millimeters):

Locality	Length, straight line	Length, along curve	Length, dorsal valve	Width, maxi- mum	Width, hinge line	Thickness
Grand Canyon.....	23	31	19	26	13	8
	32	....	....	....	....	....
	26	38	....	29	....	10
San Rafael Swell.....	22	31	....	24	....	9
	22	....	....	....	....	....

Discussion. This species apparently agrees very closely with Girty's type from the Park City formation, Permian, of Idaho, although a comparison with his figures suggests that the spines on the Kaibab forms are even more aligned and form a more regular quincunx, especially in the ventral valve. Girty refers to similar forms found abundantly in the Alaskan Artimak which he considers to be probably of this species. King describes and figures this species from the Glass Mountains of Texas.

Comparisons. *Productus humboldti irginæ* of the Bolivian Carboniferous figured by Kozłowski is remarkably similar to Girty's type and to *Waagenoconcha montpelierensis* found in the Kaibab formation, but seems to have a very definitely less restricted, wider beak, which also is less incurved. No forms exhibiting a relationship such as *P. humboldti* of Bolivia apparently has with *P. humboldti irginæ* are known to occur with *W. montpelierensis* of the Kaibab formation.

Waagenoconcha irginæ of the Cora and Schwagerina beds and of the Artinskian of Russia and Spitzbergen appears to be very similar to *W. montpelierensis* of the American Permian and, as suggested by Fredericks,⁵ may be the same. King points out that *W. irginæ* figured by Tschernyschew has a higher convexity and less blunt and less strongly inflated beak, but Tschernyschew's figures fail to convince concerning this. There does, however, appear to be a difference in the angle of divergence of the ridges on each side of sinus, that of *W. montpelierensis* being much wider. Another difference is that the Russian species has a sinus extending the entire distance to the front. Also, according to Kozłowski, it differs from the Bolivian form, *P. humboldti irginæ*, in having its spine-bearing tubercles in the middle instead of in the extreme anterior part and in having a different type of cardinal process. Whether or not the various characters enumerated are of sufficient importance to justify the making of one or more new species can only be determined by a comparison of specimens, which is not at this time possible. Should the forms prove to be the same, the name *W. irginæ* would stand because of priority.

Waagenoconcha purdoni Davidson of the upper *Productus* limestone of the Salt Range and Himalaya Mountains of India has a superficial resemblance to *W. montpelierensis* because of its similar peculiar sculpturing and shape. It is, however,

⁵ Georges Fredericks, *Sur les Productus du Carbonifère Supérieur et de l'Artinskien*, Mém. Com. Géol., new ser., book 103, p. 29, 1915.

far larger and more elongate in outline and has an arched hinge line. On the other hand, one small specimen from Bilot which Waagen figured as the same species shows rather marked resemblance in size and shape to *W. montpelierensis*, though no close comparison is possible without specimens or better figures.

Waagenoconcha waageni (Rothpletz) from Timor is similar but is far larger with concentric undulations of growth and has a wider apical angle.

Locality and horizon. Kaibab formation, β member; uncommon in facies 1 at Fossil Mountain, Hermit and Bright Angel Trails, Grand Canyon, and at Aubrey Cliffs near Seligman; very common in facies 5 at San Rafael Swell, Utah.

Specimens probably referable to this species have been listed by Girty from the following localities (numbers in parentheses refer to bibliography): 3.5 miles south of St. George (73); 15 miles south of Hurricane (73); 2.5 miles west of Virgin City in Narrows (73); Circle Cliffs (27); San Rafael Swell (20); Parusi-Wompats Spring (62); Grand Wash Cliffs (44); mouth of Grand Wash and Horse Springs (44); Aubrey Cliffs near Seligman (10). All these records are from the β member, Kaibab formation.

Avonia dorsoconcava McKee, n. sp.

(Plate 46, figures 9, 10)

Description. Shell small to medium-sized, outline subtriangular except for ears, hinge line slightly less than greatest width, which is at about mid length.

Ventral valve strongly convex with rather uniform curvature; beak small and incurved; visceral area with borders diverging greatly near beak and to less degree near anterior margin; ears definite, moderately large. Sinus present, at least on some specimens.

Dorsal valve deeply concave, nearly as large as ventral valve, shape subquadrate.

Surface covered sparingly with large spine bases or pits, fairly evenly developed. Costæ weakly developed on larger specimens.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thickness
Fossil Mountain.....	17	20	12
	14	15	9
Hilltop.....	12	14	7
	18	20	11

Discussion. Specimens representing the genus *Avonia* are abundant in the Kaibab formation but so variable in character that classification is difficult. *A. subhorrida newberryi* and *A. dorsoconcava* represent extremes in certain directions of development such as concavity of dorsal valve and convexity of umbonal area, so in well-developed specimens are seen to be quite distinctive. Many more or less intermediate forms are found, however, and, especially when poorly preserved, are very difficult to classify.

Although *A. dorsoconcava* is associated with *A. s. newberryi* in the β member of the Kaibab formation, there is no reason to confuse well-preserved specimens of this species with it. The following table shows the contrast in a number of features:

Avonia subhorrida newberryi

Dorsal valve shallow and small
 Umbonal area large, strongly convex
 Length greater than width
 Shell outline subquadrate

Avonia dorsoconcava

Dorsal valve very deep and large
 Umbonal area small, not prominent
 Width greater than length
 Shell outline subtriangular

Comparisons. Probably the American Permian form closest to this species is *A. boulei* of the Glass Mountains, which, however, is older. *A. boulei* apparently agrees in nearly every respect including the presence of a deeply concave dorsal valve; however, it has no sinus and averages larger in size.

Avonia latidorsata of the Word formation differs in many respects including a dorsal valve only moderately concave, broader proportions, and fewer spines.

Avonia subhorrida from Utah and Texas may be distinguished from this species not only by the several features listed above in the comparison with *A. s. newberryi*, but also because it has far greater size.

Locality and horizon. Typical specimens collected from the upper part of the β member, Kaibab formation, at Fossil Mountain in Grand Canyon, at Hilltop, Havasu Canyon, and at Aubrey Cliffs near Seligman.

Types. Holotype, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-650; paratypes, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-651, 652, 653, 654, 655.

Avonia subhorrida newberryi McKee, n. subsp.

(Plate 46, figure 11)

1861 *Productus costatoides*. Newberry, *Rept. upon Colo. River of the West exp. by Lieut. Ives*, pt. 3, pp. 123-124.
 Cherty limestone, banks of the Colorado.

1907 [?] *Productus latidorsatus* var. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 265-266.
 Black limestone, Guadalupian section.

Description. Shell small, transversely subquadrate. Ventral valve moderately arched. Ears small, depressed, and vaulted. Beak small, sharp, recurved very little beyond cardinal area. Hinge line slightly less than greatest width. Median sinus variable in strength but usually weak. Dorsal valve shallow, gently concave over visceral area, bent toward the margins.

Surface of shell covered with rather large, round spine bases from which in many cases develop rather coarse, indistinct costæ that die out after a short distance. Concentric growth lines show on a few specimens but actual rugæ or wrinkles seem to be entirely lacking.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Convexity
All specimens from Fossil Mountain.....	18	16	11
	20	17	12
	17	17	10
	16	15	10
	17	16	10

Discussion. This subspecies of *Avonia subhorrida*, like *A. s. rugatula* of the Guadalupe Mountains, seems to vary considerably in degree of development of various characteristics. As pointed out by Girty,⁶ the Guadalupian subspecies differs from that of the Kaibab in the presence of fine wrinkles or rugæ covering the visceral disks of both its valves. This appears to be a good diagnostic feature of *A. s. rugatula* and one which is consistently lacking on the Kaibab forms. Another difference is found in the shapes, *A. s. rugatula* being wider than long and *A. s. newberryi* being the reverse. These are, however, the only criteria for distinction that the writer has been able to observe. The general similarity between these forms and considerable variation in individuals of each to intermediate types shows clearly a close relationship. It seems possible that some of the Glass Mountain specimens from horizons lower than those represented by Girty's material are of the Kaibab type.

Regarding *Productus costatoides* Swallow, the writer agrees with Girty that in the absence of figures or of specimens of that species for comparison, it is impossible to say what affinities the upper Coal Measures (?) species has with that of the Kaibab formation. From the original description it appears that *P. costatoides* has a flattened visceral region of the ventral valve, a deep, broad sinus, large ears, and distinct costæ—characters which are not represented in *A. s. newberryi*.

Avonia latidorsata var. from the basal black limestone of the Guadalupian Mountains is said by Girty to possess the size and general expression of *A. subhorrida* var. *rugatula*, but has a fainter sinus or none at all, lacks the posterior wrinkles, and has numerous small spines over the lateral and posterior portions. From this comparison, it is obvious that this variety is very similar to and probably identical with the Kaibab subspecies, although without comparative material or figures, it is impossible definitely to determine this question.

Comparisons. *Avonia subhorrida newberryi* differs from typical *A. subhorrida* (Meek) in being considerably smaller and in having a shallower median sinus.

Avonia latidorsata (Girty) is defined as "being shorter and broader, with much fewer spines" than *A. subhorrida*. The same characteristics should serve to distinguish it from *A. s. newberryi*.

From *Avonia boulei* (Kozłowski), the Kaibab form may be distinguished by smaller size and greater convexity. Also it is proportionately narrower than that species and has a median sinus which *A. boulei* lacks.

Avonia walcottiana (Girty) is similar in size and configuration but has a very different ornamentation. It has concentric wrinkles which are fairly strong and coarse and has more numerous spines.

Locality and horizon. β member, Kaibab formation. Many specimens in Grand Canyon collection from Bright Angel and Hermit Trails and Fossil Mountain in Grand Canyon, and from Toroweap Valley. Specimens examined in U. S. Geological Survey collection from Narrows of Virgin River and from 3.5 miles south of St. George.

In published faunal lists covering brachiopod collections from the Kaibab formation, this genus is nearly always represented (numbers in parentheses refer to bibliography): Specimens from Parusi-Wompats Springs (62) and some from Goodsprings Quadrangle, Nevada (32) have been referred to *A. subhorrida* var. *rugatula*; those from Aubrey Cliffs (10) and from Grand Wash Cliffs (44) to *A. subhorrida*; while those from Beaver Valley (38) and some from Goodsprings (32)

⁶ G. H. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 266, 268, 1907.

have been designated as aff. *subhorrida*. It is probable that both *A. s. newberryi* and *A. dorsoconcava*, possibly also with other varieties, are represented.

Types. Holotype, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-660; paratypes, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-661, 662, 663, 664, 665, 666.

Marginifera meridionalis McKee, n. sp.

(Plate 47, figures 1-5)

Description. Shell medium-sized (large for the genus), wider than long, subquadrate; hinge line about equal to greatest width of the shell; character of ears little known.

Ventral valve of low convexity, depressed in posterior part, but strongly geniculate. Beak fairly prominent; umbonal slopes steep. In many specimens a long trail has developed with straight, parallel sides, giving the anterior part of the shell a narrow rectangular appearance. In about half of the Kaibab specimens the trail is missing, so the remaining free shell, being mostly posterior to the geniculation, assumes a very different appearance. The visceral chamber in mature specimens is largely posterior to the hinge line. A well-defined, rounded sinus begins a short distance in front of the beak and continues with rather uniform width to the anterior margin.

Dorsal valve has a rather small, flat visceral disk with a strong geniculation not far from the anterior margin. Inside, at the line of geniculation there appears to be a raised marginal ridge.

Surface of both valves marked by fine, even costæ, about 30 in number or 5 to the space of 5 mm. They are separated by fine sulci and on the visceral disk of each valve are crossed by even concentric rugæ of about the same strength. Small spine bases are found scattered sparingly over both valves.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thick- ness	Locality	Length	Width	Thick- ness
Fossil Mountain.....	19	21	12	Hilltop.....	22	27	10
	21	26	13		20	25	13
	24	24	11		22	28	9
	19	22	9	Hermit.....	23	24	11
					22	24	11

Discussion. This large species of *Marginifera* is quite distinctive because of its fine costæ which form a gridlike pattern with the rugæ on its visceral disks, because of its strong geniculation, and especially because of its long, non-flaring trail. In these respects it more closely resembles *M. lasallensis* of the Pennsylvanian (see Dunbar and Condra for description) than any of the species yet described from the Permian.

Comparisons. Small specimens without the trail somewhat resemble *M. popei* with which they are found associated in the Kaibab formation, in size and shape, but may be distinguished readily by the much finer costæ, which extend practically to the beaks, by the development of concentric rugæ, and by several other minor features.

Other Permian species which somewhat resemble *M. meridionalis*, especially when its trail is missing, are *M. texana*, *M. reticulata*, and *M. opima*. The first of these has costæ of about the same size and number but differs in not having the well-developed rugæ on visceral disks of both valves. It is a smaller form and probably never develops the long trail of this species. *M. reticulata* and *M. opima* may both be readily distinguished by fewer, coarser costæ (*M. reticulata*, 18 to 20; *M. opima*, 21 to 28) as well as by several other features.

Locality and horizon. Common in facies 1 of β member, Kaibab formation. Many specimens in Grand Canyon collection from Fossil Mountain in Grand Canyon and Hilltop at Havasu Canyon. The specimens from Bronze-L mine, Grand Wash Cliffs, referred to *Productus lasallensis*? by Girty (44) are probably of this species. Possibly also his *M. splendens* from northwestern Arizona (73) is of this species.

Types. Cotypes, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-670, 671, 672, 673, 674, 675, 676.

Marginifera popei (Shumard)

(Plate 47, figures 6-8)

- 1858 *Productus popei*. Shumard, Trans. Acad. Sci. St. Louis, vol. 1, p. 290 (date of volume, 1860).
Permian, New Mexico and Texas.
- 1859 *Productus popei* (ex parte). Shumard, Trans. Acad. Sci. St. Louis, vol. 1, p. 389, pl. 11, figs. 8-8b.
White (Permian) limestone, Guadalupe Mountains.
- 1908 *Productus popei*. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 257-258, pl. 20, figs. 9-11b.
Dark limestone, Pine Spring; Delaware Mountain formation, southern Delaware Mountains.
- 1930 *Marginifera popei*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 88, pl. 22, figs. 16-19.
Word, Vidrio, Leonard, and Hess (?) formations, Glass Mountains.

Description. Shell small, subquadrate, wider than long, greatest width at cardinal border. Ventral valve strongly arched, forming slightly more than a semi-circle and having summit near or somewhat posterior to mid length. Beak small, incurved. Median sinus prominent, narrow. Ears small. Dorsal valve subquadrate, concave, sometimes with low median fold.

Surface of both valves covered with coarse rounded costæ separated by equally coarse sulci. On ventral valve costæ average 3 to the space of 5 mm. or make a total of about 18 or 20. A few spines are scattered over the surface along the costæ. Some costæ are bifurcate; all are weakly developed or absent near posterior margin.

Measurements. Ventral valve of specimen from Fossil Mountain in Grand Canyon measures (in millimeters): length, 18; width, 24; thickness, 9. Dorsal valve from Macks Crossing (East Clear Creek) on Mogollon Plateau: length, 15; width, 23; thickness, 6.

Discussion. As pointed out by King, "this species is distinguishable from other productids in the fauna by the combination of its small size, bilobate form, strong costæ, and by the absence of reticulation on the posterior part." When developed, the median fold on the dorsal valve is probably also a good criterion.

Comparisons. This species appears to be closely related to *Productus occidentalis* but is only about half its size, has relatively coarser ribs, and probably differs somewhat in shape.

King compares it to *Marginifera typica* Waagen, which he says differs in having smaller costæ and reticulation near the beak.

Locality and horizon. Uncommon but present in several facies of β member, Kaibab formation. Specimens in Grand Canyon collection from facies 1 at Fossil Mountain, Grand Canyon; facies 4 at Macks Crossing (East Clear Creek), Mogollon Plateau; facies 4 at Padre Canyon, east of Flagstaff. Also, specimens in the Grand Canyon collection from Upper Nutria Pueblo, Zuni Reservation, New Mexico (San Andreas Co.) appear to be identical in every respect.

Specimens from 1 mile southwest of Ohio Oil Company well at Circle Cliffs were listed by Girty (27) as *Productus* aff. *P. popei*.

Pugnoides pinguis (Girty)

(Plate 47, figures 10-12)

1908 *Pugnax pinguis*. Girty, *The Guadalupean fauna*, U. S. Geol. Surv. Prof. Paper 58, p. 319, pl. 21, figs. 21-21c.

Dark limestone, Pine Spring.

1930 *Pugnoides pinguis*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 106, pl. 34, figs. 15-17.

Hess, Leonard, and Word formations, Glass Mountains.

Description. Shell medium-sized, subpentagonal with anterior margin quite rounded.

Ventral valve comparatively flat with small, erect beak and definite broad, shallow median sinus developed in anterior half. Sinus extends forward and upward as a tongue and near front stands at approximately a right angle to the plane of the shell margin. Rounded, thin, high plications occur over the anterior half but die out about two-thirds the distance to the beak. There are usually 2 on the fold and 4 or 5 lateral ones on each side.

Dorsal valve deep, flattened over median part except near margins, where strongly curved. Fold begins about mid length but is prominent only near anterior margin. Plications as on ventral valve, with 3, sometimes 4, on the fold.

Measurements. Typical specimens:

Locality	Plications on fold	Plications on sinus	Lateral plications (each side)	Length (mm.)	Width (mm.)	Thickness (mm.)
Girty's type.....	4	3	4-5	13	14.5	....
Fossil Mountain.....	3	2	4	13	15	9
	4	3	5	14	15	9
	....	2	5	....	14	....
	....	2	5	14	15	....
Bright Angel.....	3	....	4	11	12	7
	....	2	3	8	8	6
Point Sublime.....	3	2	3	9	10	7
	3	2	4	10	10	6
	3	2	3	9	8	4
	....	2	4	9	9	7
	....	3	4	11	12	....

Discussion. Among the most distinctive characters of this species are flatness of the ventral valve, the straight rather than incurving projection of the beak, and the marked geniculate character of the sinus.

Two series of *Pugnoides* in the Grand Canyon collection—one from near Point Sublime, the other from west of the Bright Angel Trail—have been referred to this species with some doubt. In both instances they represent small forms comparable in size with *P. bidentatus* or *P. swallowianus* of the Texas Permian, yet differing from each in several respects. They may readily be distinguished from the former by the presence of more lateral plications and by far less gibbous form. From the latter they differ chiefly in having a flat or shallow ventral valve and an erect beak.

At the present time it seems best to consider the small forms of *Pugnoides* just mentioned as representing merely a variety of *P. pinguis*, dwarfed and less developed because of an environment closer to near-shore, brackish-water areas. Its distribution in the formation and the occasional occurrence with it of a somewhat larger shell with better-developed lateral plications tends to confirm this.

Comparisons. This species resembles *P. shumardianus* in general size and shape but differs in having fewer plications on fold and sinus and better-developed lateral plications, averaging more in number. Also, it is relatively narrower than that species.

The well-known Pennsylvanian form *P. osagensis* is smaller and has less prominent and fewer lateral plications. *P. osagensis* var. *occidentalis* of the Phosphoria has great similarity, being comparable in size and strength of plications. Although King referred it to *P. swallowianus*, the writer believes that it is closer to *P. pinguis*. A difference of questionable importance is the frequent occurrence in it of only two plications on the fold, a feature not yet observed on the Kaibab forms under discussion.

Of the other American Permian forms which are of comparable large size, *P. elegans* and *P. transversus* may readily be distinguished from this species by their very different shapes and proportions as well as by other features which need not be discussed here.

Locality and horizon. Upper part of β member, Kaibab formation. Specimens in Grand Canyon collection are from Fossil Mountain, from west of Bright Angel Trail, and from near Point Sublime, Grand Canyon. Also, this form has been recorded from Toroweap Valley by the writer.

In published faunal lists specimens of *Pugnoides*, presumably of this species, have been listed as follows (numbers in parentheses refer to bibliography): *P. osagensis* var. from Parusi-Wompats Spring (62) and from mouth of Rock Canyon on Uinkeret Plateau (73); *P. aff. osagensis* from Beaver Valley (38); *Pugnoides* n. sp. ? from Aubrey Cliffs near Seligman (10).

Spirifer (Neospirifer) pseudocameratus Girty

(Plate 47, figures 13, 14)

1859 *Spirifer cameratus*. Shumard, Trans. Acad. Sci. St. Louis, vol. 1, p. 391 (date of volume, 1860).

(Permian) sandstone and white limestone, Guadalupe Mountains.

1908 *Spirifer* sp. b. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 363-364.

Delaware Mountain formation: Guadalupe Point, southern Delaware Mountains; "Comanche Canyon," Glass Mountains.

- 1920 *Spirifer pseudocameratus*. Girty, in *Ore deposits of Utah*, U. S. Geol. Surv. Prof. Paper 111, pp. 644-645, pl. 56, figs. 10-15.
Permian, Utah.
- 1930 *Spirifer pseudocameratus*. C. Branson, *Paleontology and stratigraphy of the Phosphoria formation*, Univ. Missouri Studies, vol. 5, no. 2, p. 35, pl. 6, figs. 6-8.
Pustula member, Wind River and Owl Creek Mountains, Wyoming; Rex chert member, Utah and Idaho.
- 1930 *Spirifer* (*Neospirifer*) *pseudocameratus*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 116, pl. 38, figs. 4-6, pl. 39, figs. 1-3.
Leonard and Word formations, Glass Mountains; Bone Canyon member, Victorio Peak member, Sierra Diablo; Victorio Peak member, Brackett Draw; Leonard formation, Shafter; Leonard formation, Baylor Mountains; Delaware Mountain formation, Sierra Diablo; limestone of Cerro Caballo, Las Delicias.

Description. Shell fairly large, wider than long, not alate. Maximum width at hinge line. Cardinal angles vary in degree of acuteness with proportionate narrowness of shell.

Ventral valve convex, especially in umbonal region; beak small and incurved. Cardinal area moderately high and curving out at angle oblique to plane of shell margin. Sinus moderately deep and narrow; contains several small costæ within.

Dorsal valve moderately convex. Fold definite but variable in prominence; sometimes low, in other instances fairly high and narrow; divided by small groove between two costæ, each of which bifurcates on outer margins and proceeds anteriorly like other costæ.

Lateral slopes of both valves are strongly marked with ribs each of which contains several costæ. The costæ vary considerably in size and prominence, in some instances having one major and two minor ones to a rib, elsewhere appearing with about equal prominence on all ribs. Six or eight fascicles of three costæ each are usually present near the beak, but the number of costæ increases anteriorly.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thickness
S. of Wickiup, San Rafael Swell	43	66	33
	50	70	....
	40	60	....

Discussion. This brachiopod has not been found, to the writer's knowledge, in any part of the Kaibab formation except facies 5 of the β member, which occurs as outcroppings in southeastern Utah. There, specimens of it are locally very abundant, but poorly preserved in nearly every instance. Although Girty gave only "Utah" as locality, it seems not unlikely that the material from which he described this species may have come from one or more of the areas represented in the Grand Canyon National Park collection.

The distribution in the formation of this and associated species such as *Wagenoconcha montpelierensis* suggests a close relationship between this facies and the *Pustula* and Rex chert members of the Phosphoria formation. If, therefore, the facies truly represents a part of the Kaibab formation, as has long been assumed, then these two formations, despite their largely dissimilar faunas, are to be correlated and the faunal differences explained as due to distinct environments.

Comparisons. Both Girty and King have discussed the similarity and the differences between this species and *Spirifer cameratus* and *S. triplicatus* of the Pennsylvanian. They point out that *S. pseudocameratus* is "generally somewhat larger, with commonly a greater relative length, coarser, more irregular costæ, and a narrower and lower fold and sinus."

Locality and horizon. Very common in facies 5 of the β member, Kaibab formation, at San Rafael Swell, Utah (9.5 miles south of Wickenburg) and at south end of Teasdale anticline (canyon of Pleasant Creek) 6 miles south of Fruita, Utah.

A spirifer from the Kaibab formation at Beaver Valley, Utah, has been listed by Girty (38) as *S. aff. cameratus* and another from mouth of Rock Canyon on Uinkaret Plateau simply as *Spirifer* sp. (73). These appear to be the only references, even to the genus, in the literature on the Kaibab formation.

Squamularia guadalupensis (Shumard)

(Plate 48, figures 1-3)

- 1859 *Spirifer guadalupensis*. Shumard, Trans. Acad. Sci. St. Louis, vol. 1, p. 391 (date of volume, 1860).
White (Permian) limestone, Guadalupe Mountains.
- 1861 *Spirifer lineatus* in part?. Newberry, *Rept. upon Colo. River of the West exp. by Lieut. Ives*, pt. 3, p. 127.
Upper Carboniferous: cherty limestone west of Little Colorado River; vicinity of Santa Fe, New Mexico.
- 1908 *Squamularia guadalupensis*. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 367-369, pl. 14, figs. 4-11a.
Middle Capitan, Capitan Peak; basal Capitan, hill southwest of Guadalupe Point; Delaware Mountain formation, southern Delaware Mountains; Delaware Mountain formation, "Comanche Canyon," Glass Mountains.
- 1909 *Squamularia perplexa*?. Girty, *Fauna of the Manzano group*, U. S. Geol. Surv. Bull. 389, pp. 66-68.
Yeso formation, Mesa del Yeso; San Andres formation, San Andres.
- 1930 *Squamularia guadalupensis*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, pp. 118-119.
Wolfcamp formation, Glass Mountains; Hess formation, Glass Mountains, common; Leonard formation, Glass Mountains, common; Word formation, Glass Mountains; Altada member, Glass Mountains, abundant; Bone Canyon member, Sierra Diablo; Victorio Peak member, Sierra Diablo; Leonard formation, Shafter, common; Word formation, Shafter.

Description. Shell medium-sized to large, subovate. On large specimens length slightly greater than width, on small specimens about the same. Cardinal area large and triangular, hinge line somewhat more than half the greatest width, which is at mid length. Well-preserved specimens show no ventral median sinus, but exfoliated ones usually show this feature rather prominently toward the front of the inner shell.

Ventral valve high with long, definitely incurved beak. Dorsal valve about equally high on large specimens, lower on small ones; outline transversely oval. Dorsal beak incurved and projecting slightly beyond cardinal margin.

Outer shell surface marked by narrow, regular, concentric bands which presumably were once covered with numerous minute, flat-lying spines extending forward. Since the outer shell is very thin, it is seldom well preserved, so on most specimens appears to be covered at regular intervals with liræ which cross the bands.

Measurements. Typical specimens of three sizes (in millimeters):

Locality	Length	Width	Thickness
Fossil Mountain:			
Very large specimen.....	29	25	24
Large specimen.....	24	22	19
Average specimen.....	20	20	15

Discussion. Specimens of *Squamularia guadalupensis* from the Kaibab formation apparently agree very closely with those described by Girty from the Guadalupe formation of Texas. Those from the Glass Mountains of Texas described by King are likewise similar, although from his measurements they appear to be proportionately wider. Among the Kaibab specimens there is a tendency toward elongation and a more rotund development in the larger forms, with the result that they approach Girty's variety *ovalis* in appearance. From a series of specimens showing intermediate forms it is apparent, however, that these represent stages in development. Since Girty was quite hesitant concerning the validity of his variety, it is probable that his case was parallel to this. Girty's other variety of *S. guadalupensis*, called *subquadratus*, was distinguished by its subquadrate form due to the development of a sinus on the ventral valve. Specimens definitely referable to this variety have not been found in the Kaibab formation.

Comparisons. In America the Pennsylvanian form, *S. perplexa*, from the Mississippi Valley may be best distinguished from *S. guadalupensis* by its different type of ornamentation. Even though the spines are weathered off from the Kaibab form, the difference is apparent from the lack of double-barreled spine bases and from the presence of lira-like markings at uneven intervals over the surface. *S. setigera* Hall of the Pennsylvanian is less gibbous and has both a fold and a sinus, which readily distinguish it.

From the Salt Range fauna of India two species of *Squamularia* which have somewhat similar appearance have been described. *S. elegantula* Waagen is proportionately thinner and wider and has a different type of ornamentation. *S. indica* is very similar but is much larger, being about twice the size of the Kaibab specimens of *S. guadalupensis*; it has an exceptionally large triangular fissure and a rather distinct sinus. *S. lineata* Mart., described from Europe and also found in the Salt Range, is proportionately much wider and is a large shell with a fairly small triangular fissure.

Locality and horizon. Kaibab formation, β member, common. Specimens have been recorded by the writer from Bright Angel Trail and Fossil Mountain in Grand Canyon, from Hilltop, Aubrey Cliffs near Seligman, House Rock Valley, and near Clover Creek on the Mogollon Plateau. Other specimens examined⁷ were from: The Narrows, 2.5 miles south of St. George; Kanab Canyon, 13 specimens; Shimumo Canyon, 7 specimens; Ochre Springs, Kaibab Plateau, 8 specimens.

Kaibab formation, α member. Specimens have been examined as follows: Beaver Dam Mountains, 2 specimens; 4 miles south of St. George, 2 specimens; 2 miles southeast of Black Rock Spring, 20 miles south of Bloomington, 8 specimens.

In published faunal lists specimens of *Squamularia* have been listed as follows (numbers in parentheses refer to bibliography): *S. guadalupensis*, northwestern Arizona and southwestern Utah, α and β members (73); *S. guadalupensis*?,

⁷ Specimens in U. S. Geological Survey collection which have been examined by the writer.

β member, Parusi-Wompats Spring (62) and Aubrey Cliffs near Seligman (10); *S. aff. guadalupensis*, Grand Wash Cliffs at Bronze-L mine (44); *Squamularia* ? sp., Kaibab β member at Circle Cliffs (27) and Toroweap β member at Beaver Valley (38); *S. aff. perplexa*, Kaibab β member at Beaver Valley; *S. perplexa*, Kaibab β member at House Rock Valley, Toroweap and Hurricane fault scarp (77)

Spiriferina hilli Girty

(Plate 48, figures 4-6)

1908 *Spiriferina hilli*. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, p. 379, pl. 30, figs. 15-15b.
Delaware Mountain formation, "Comanche Canyon," Glass Mountains.

1915 *Spiriferina hilli*. Haack, *Permfauna aus Nordmexiko*, Ztschr. Deutsch. Geol. Gesell., vol. 66 (1914), pp. 495-497, pl. 39, figs. 2-9.
Pichagua, near Las Delicias.

1930 *Spiriferina hilli*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 122, pl. 42, figs. 1-6.
Hess and Leonard formations, Glass Mountains; Leonard formation, transition beds, Shafter; limestone of Pichagua, Las Delicias.

Description. Shell small with greatest width slightly anterior to hinge line, wider than long. Cardinal area high, usually close to right angle with plane of shell margin. Beak incurved. Foramen narrow and high.

Ventral valve with sinus resembling lateral sulci but broader. Lateral plications 4 to 6 on each side, decreasing in size laterally. A low median plication may be present, according to Girty, but has not been noted in any of the Kaibab specimens. Plications bordering the sinus are distinctly larger than others.

Dorsal valve wider than long, with small incurved beak. Lateral plications, 4 or 5 on each side, resemble those of ventral valve. Median fold similar to plications but somewhat larger and slightly flattened on top anteriorly.

Surface smooth except for occasional and irregularly distributed growth varices on all specimens examined. Shell structure said to be slightly punctate.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thickness
Bright Angel Trail.....	10	14	....
	8	13	....
Fossil Mountain.....	8	14	....
	12	20	11

Discussion. In a general way, especially in size and proportions, this species resembles the well-known Pennsylvanian species *Punctospirifer kentuckyensis*. It may readily be seen to be different and even to belong to another genus, however, since it has a fold and sinus which are narrow, subangular, and differing from lateral plications only in size, since it lacks well-marked concentric lamellæ, and since it has fewer plications.

The assignment of the Kaibab forms to *Spiriferina hilli* is not without some doubt, since Girty refers to a low median plication in his type and suggests that it is of importance as a distinguishing characteristic. Since his description was based on a single specimen, the only one then known to represent the species, it seems

probable that the median plication is not a constant feature, especially since King's specimens from the same area apparently do not have it. The marked similarity in other features leads the writer to consider this reference to *S. hilli* desirable.

Comparisons. There are no American Permian species which are likely to be confused with *S. hilli* because of its very small size and its proportions of width to length. Girty has compared it with *S. cristata*, which he considers the closest foreign relative, and Haack has discussed its similarity to *S. multiplicata* (Sowerby), thought by him to be a closer relative.

Locality and horizon. This species is fairly common at several horizons in the upper part of the β member, Kaibab formation, in the Grand Canyon region. Specimens in the Grand Canyon National Park collection are from Fossil Mountain and from west of Bright Angel Trail. Others that have been examined by the writer are from Hilltop at Havasu Canyon, Aubrey Cliffs near Seligman, and the divide between Clover and Pivot Creeks on the Mogollon Plateau.

In published faunal lists specimens of *Spiriferina* have been listed as follows (numbers in parentheses refer to bibliography): *S. campestris*, Goodsprings Quadrangle, Nevada (32), 3 miles south of Jacob's Lake (77), Hurricane Ledge (77), and Aubrey Cliffs at Seligman (10); *S. campestris*?, Parusi-Wompats Spring (62); *S. kentuckyensis*, House Rock Valley (77); *S. aff. kentuckyensis*, Beaver Valley (38); *Spiriferina* sp., Circle Cliffs (27), Beaver Valley (38), and The Narrows, 2.5 miles west of Virgin City (73). The preceding references are all to the β member, Kaibab formation. From the α member *Spiriferina* sp. has been recorded at Beaver Dam Mountains (73).

Punctospirifer? sp.

(Plate 48, figure 7)

Discussion. In the collection of Grand Canyon National Park is one large specimen of Spiriferida which is sufficiently distinctive to warrant mention. It is the internal mold of the dorsal valve of a form which because of its wide, flat sinus, especially in comparison with its lateral sulci, and because of the number of its plications, is tentatively referred to the genus *Punctospirifer*.

Distribution. The specimen at hand is from the β member of the Kaibab formation, Fossil Mountain in Grand Canyon.

Hustedia meekana (Shumard)

(Plate 48, figures 8, 9)

1858 *Retzia* (?) *meekana*. Shumard, Trans. Acad. Sci. St. Louis, vol. 1, p. 295 (date of volume, 1860).

White and dark (Permian) limestone: Guadalupe Mountains; conglomerate at the mouth of Delaware Creek.

1859 *Retzia meekana*. Shumard, Trans. Acad. Sci. St. Louis, vol. 1, p. 395, pl. 11, fig. 7a, b.

White and dark limestone: Guadalupe Mountains; conglomerate at the mouth of Delaware Creek.

1908 *Hustedia meekana*. Girty, *The Guadalupian fauna*, U. S. Geol. Surv. Prof. Paper 58, pp. 394-396, pl. 14, figs. 22-26a, pl. 21, figs. 5-8a, pl. 24, figs. 14, 14a, pl. 29, fig. 8, pl. 30, figs. 16, 17.

Top of Capitan, middle Capitan, Capitan Peak; basal Capitan, hill southwest of Guadalupe Point; dark limestone, Pine Spring, Guadalupe Point, hill southwest of Guadalupe Point; basal black limestone, Guadalupe Point; Delaware Mountain formation, southern Delaware Mountains; Delaware Mountain formation, "Comanche Canyon," Glass Mountains.

1915 *Retzia (Hustedia) meekana*. Haack, *Permfauna aus Nordmexiko*, Ztschr. Deutsch. Geol. Gesell., vol. 66 (1914), pp. 497-501, text-figs. 1, 2, pl. 39, fig. 10a-c.

1930 *Hustedia meekana*. King, *The geology of the Glass Mountains, Texas*, Univ. Texas Bull. 3042, pt. 2, p. 126, pl. 42, figs. 34-39.

Hess, Leonard, and Word formations, Glass Mountains; Altuda member, Glass Mountains; Bone Canyon member, Delaware Mountains; Victorio Peak member, Sierra Diablo; Leonard formation, Baylor Mountains; Delaware Mountain formation, Sierra Diablo; Leonard formation, Shafter; limestone at Cerro Callo, Las Delicias; limestone of Pichagua, Las Delicias.

Description. Shell fairly small, ovate, gibbous, longer than wide, valves nearly equally convex, anterior portion of sides and front regularly rounded. Ventral valve high with beak prolonged, incurved (?). Dorsal valve with beak small, incurved.

Surface of both valves marked with radiating plications, ventral with 10 or 11 and dorsal with 9 or 10. Plications expand gradually from origin to borders and are separated by deep sulci as wide as themselves. Both are large and subangular.

Measurements. Specimen from west of Bright Angel Trail (in millimeters): length, 10.5; width, 8; thickness, 7.

Discussion. Only one specimen of this genus is represented in the Grand Canyon collection. It is fairly well preserved, however, and is referred to the species *meekana* without hesitation. Since the specimen is silicified, none of the faint liræ which Shumard found superimposed on the costæ of his exfoliated specimens, and which he considered an important specific character, are to be seen.

Comparisons. *Hustedia meekana* differs from *H. mormonii* and *H. m. papillata* (which appear to be essentially the same or very nearly so) in consistently having fewer and larger plications. It is a somewhat larger form and is said to have a more elongate and erect beak.

Hustedia bipartata may readily be distinguished from this species by a median depression in the dorsal valve, but in other respects it seems to be the same. It has, therefore, been suggested by King that *H. bipartata* is actually only a variety of *H. meekana*.

Hustedia huecoensis is different from *H. meekana* in numerous respects, notably in having many more plications, a low convexity, and a length about equal to its width.

Eumetria indica, described by Waagen, has been shown by Haack to be very similar to *H. meekana*. He considers that the Indian form has smaller costæ, more strongly convex ventral valve, and greater length in relation to width, but King questions whether the differences are even sufficiently great to constitute a new variety.

Locality and horizon. Upper part of β member, Kaibab formation; west of Bright Angel Trail, Grand Canyon; 2 miles southwest of Flagstaff.

In published faunal lists *Hustedia* aff. *meekana* has been listed from β member of both Kaibab and Toroweap formations at Beaver Valley, Utah (38).

Composita arizonica McKee, n. sp.

(Plate 48, figures 10-16)

- 1858 [?] *Terebratula subtilita* (in part). Marcou, *Geology of North America*, p. 51, pl. 6, figs. 9-9f.
Mountain limestone, Sierra de Magoyon, etc.
- 1861 [?] *Athyris subtilita* (in part). Newberry, *Rept. upon Colo. River of the West exp. by Lieut. Ives*, pt. 3, p. 126.
Upper Carboniferous: cherty limestone on banks of Colorado between Little Colorado and Diamond Rivers; Pecos village, east of Santa Fe.
- 1875 [?] *Spirigera subtilita* (in part). White, U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 4, p. 141, pl. 10, fig. 6a-c (whole volume published in 1877).
Carboniferous: Tenney's Ranch, Kaibab Plateau, etc.

Description. Shell small, pentagonal, greatest width about half or slightly more of the distance from the beak to the front. The relation of length to width varies somewhat. Commonly the width is about four-fifths the length, occasionally equal to it, but never greater. Ventral beak large and prominently incurved. Both valves strongly convex.

Ventral valve with wide, flat area developed at the anterior end. This is so shallow that it can scarcely be considered a true sinus, and there is no median groove. In well-developed specimens the flat median area extends forward as a prominent tongue with nearly parallel sides, fitting the elevated and extended fold of the dorsal valve.

Dorsal valve has no median sinus but anteriorly has a broad, slightly rounded median fold limited by two well-developed lateral sinuses.

The surface is smooth except for concentric growth lamellæ, which are commonly crowded together toward the front. Exfoliated specimens show an under surface covered with minute pustules, giving a suggestion of striation.

Like other members of this genus, *Composita arizonica* appears to be quite variable. Much of this variability, however, represents stages in development and conditions of preservation. Specimens of only 12 or 13 mm. length have median ridge and sinus and dorsal lateral sinuses very slightly or not at all developed, although strangely enough they often have very produced anterior tongues as in the larger shells. Specimens smaller than this are usually rounded and without the diagnostic features of the species. Occasionally specimens which appear to be abnormally or excessively developed are found. These have the normal width but are considerably longer than average specimens. Their relationship is definitely shown, however, in a series of growth plications, the posteriormost of which has the outline of a normal specimen.

Measurements. See table on next page.

Discussion. As listed in the synonymy, and also in the tabulation of faunal-list references, which follows, specimens of the genus *Composita* have been collected in the Colorado Plateau area, presumably from the Kaibab formation, and referred to the species *subtilita* numerous times. Although in none of these cases were the particular specimens specifically described or figured, it is probable that in many cases they were *C. arizonica*, here described, since this is by far the most common member of this genus in the Kaibab formation.

This species is probably also represented in other Permian formations of western America, but has not heretofore been differentiated from *C. subtilita* or other species. Certain diagnostic features such as lack of median sinus, extended tongue, size, and general shape should serve to differentiate *C. arizonica* from all other species and varieties. For an excellent description of the character of true *C. subtilita* the reader is referred to Dunbar and Condra.

TYPICAL SPECIMENS (IN MILLIMETERS)

Locality	Length	Width	Thick- ness	Locality	Length	Width	Thick- ness
Fossil Mountain, Grand Canyon, β member....	19	17	11	Ochre Spring— <i>Continued</i>	17	15	10
	19	17	11		19	16	12
	20	18	12		17	15	12
	18.5	18	11.5		18	16	10
	18	16	10		18	17	9
	17	17	11	Kanab Canyon, β member.....	18	17	11
	16	15	9		18	16	11
	18	17	10		20	19	12
	17	13.5	11		17	16	8
	18	14	11		18	15	10
	18	14	11		18	16	10
	16.5	13	10	Rock Canyon mouth, 0.5 mi. W. of Hurricane-Antelope Road, α member*.....	18	15	12
	15	11.5	9.5		16	13	11
	16	13	10		19	18	10
	17	14	10		16	14	9
	17	14	10		14	12	9
	16	13	9		15	13	10
	16.5	14	9.5	Beaver Dam Mountains, 1 mi. S. of highway, α member.....	18	17	10
Ochre Spring, Kaibab Plateau, β member....	20	18	10				
	19	18	12				
	18	18	9				
	17	14	10				
	21	18	14				

*Also many which appear to be young, about size of last two. No tongues or poorly developed; without ridges or sinuses; "round stage."

Comparisons. Among the known Permian forms, *Composita mexicana* (Hall) seems to approach the common Kaibab variety most closely. It is even smaller in the mature stages, but is likewise pentagonal in shape and has an extended anterior tongue and a high dorsal fold made prominent by depressions on each side. The chief difference seems to be in the consistently greater size of *C. arizonica* and in its total lack of median sinus. In large series of specimens the adult form of this species ranges between 16 and 20 mm. in length, while in typical mature *C. mexicana* the length is always 15 mm. or less. According to description, the anterior median parts of the ventral valve in *C. mexicana* are marked by a narrow groove or sinus "producing a strong forward and upward deflection of the anterior margin," while no true sinus is present in *C. arizonica*.

The rather variable form from the Upper Carboniferous of Bolivia, referred to *Seminula argentea* by Kozłowski and admirably illustrated, shows some resemblance to *C. arizonica*, especially in the ventral view, which shows a flat, extended tongue. The small average size is likewise similar, but the more rounded shape and proportionately greater width as seen in the dorsal valve are decidedly different; also the median ridge and lateral sinuses are less prominent.

REFERENCES TO *Composita* IN PUBLISHED FAUNAL LISTS

Locality	Horizon	Name used	Determined by	Reference *
Parusi-Wompats Spring, N. of Shinumo Quad.....	"B" horizon	<i>Composita subtilita</i>	G. H. Girty	(62)
Beaver Dam Mtns.....	Lower strata of Harrisburg gypsiferous member	<i>Composita subtilita</i>	G. H. Girty	(73)
Hurricane fault scarp, 18 mi. S. of Hurricane.....	Massive limestone member	<i>Composita mexicana?</i>	G. H. Girty	(73)
15 mi. S. of Hurricane, 2 mi. W. of Virgin City.....	Massive limestone member	<i>Composita subtilita</i>	G. H. Girty	(73)
Aubrey Cliff, NW. of Seligman.....	.....	<i>Composita subtilita</i>	G. H. Girty	(10)
Lower Canyon, Kanab Creek, Ariz.; east front, Spring Mtn. Range, Nev.....	Middle limestone	<i>Athyris subtilita</i>	G. K. Gilbert	(17)
1 mi. SW. of Ohio Oil Co. well, Circle Cliffs, Utah.....	10-15 ft. above bed 2	<i>Composita</i> sp.	G. H. Girty	(27)
3 mi. S. of Ohio Oil Co. well, Circle Cliffs, Utah.....	Upper part of bed 3	<i>Composita</i> sp.	G. H. Girty	(27)
3 mi. S. of Ohio Oil Co. well, Circle Cliffs, Utah.....	50 ft. lower	<i>Composita</i> sp.	G. H. Girty	(27)
Head of Black Box, San Rafael River, Utah.....	Just below Moenkopi	<i>Composita</i> sp.	G. H. Girty	(20)
Head of Black Box, San Rafael River, Utah.....	Coquina limestone below Moenkopi	<i>Composita mexicana?</i>	G. H. Girty	(20)
4 mi. SE. of Bronze-L mine near Muddy Mtns.....	Top of upper cliff	<i>Composita subtilita</i>	G. H. Girty	(44)
Near mouth of Grand Wash.....	.....	<i>Composita subtilita</i>	G. H. Girty	(44)
Weiser Ridge, 2 mi. S. of Narrows, Ariz.....	.....	<i>Composita mexicana</i>	G. H. Girty	(44)
Beaver Valley, Utah.....	Upper cherty limestone	<i>Composita aff. subtilita</i>	G. H. Girty	(38)
2 mi. S. of Flagstaff.....	Limestone	<i>Composita subtilita</i>	H. W. Shimer	(77)
House Rock Valley.....	Bed 7; bed 12	<i>Composita subtilita</i>	H. W. Shimer	(77)
Hurricane, S. of Virgin River, along fault.....	Below Moenkopi shales	<i>Composita subtilita</i>	H. W. Shimer	(77)
N. of Fort Apache.....	.....	<i>Athyris subtilita</i>	A. B. Reagan	(72)
Goodsprings Quad., Nev.....	.....	<i>Composita subtilita</i>	G. H. Girty	(32)
Castle Valley, Utah.....	<i>Bellerophon</i> limestone	<i>Composita mexicana?</i>	G. H. Girty	(49)

* Numbers refer to bibliography.

Locality and horizon. Kaibab formation, β member, abundant. Many specimens have been examined by the writer from Fossil Mountain, Point Sublime, and Bright Angel and Hermit Trails in Grand Canyon, from Shinumo and Kanab Canyons, and elsewhere in facies 1 and 2. Specimens from α member at Beaver Dam Mountains and south of Hurricane, Utah, appear to be identical, and likewise one from α member at lower end of Black Box Canyon, San Rafael Swell, Utah.

For references in published faunal lists, see the accompanying table.

Types. Cotypes, Grand Canyon Nat. Park Mus., Grand Canyon, Arizona, FK-680, 681, 682, 683, 684, 685, 686, 687.

Composita arizonica var.

Discussion. In the Kaibab formation, although most *Compositas* of the type with pentagonal shape, no sinus, and flat extended tongue are of the moderately large form here designated as *arizonica*, certain others which are far smaller, but apparently fully developed, also occur. No doubt these forms, because of their small size, are the ones which have previously been referred to *C. mexicana*; however, if a well-developed sinus is a characteristic of that species, the small Kaibab forms should be referred to *C. arizonica*. Almost certainly they represent a variety of it dwarfed by certain environmental features.

The writer has examined a series of *Compositas* of this variety collected by J. B. Reeside from the Narrows about 2 miles west of Virgin City, Utah. They were found about 175 feet below the top of the Kaibab formation. Although having fully developed extended tongue and lateral sinuses, mature forms in this series reached a maximum length of only 15 mm., in contrast with the consistently greater length of specimens of typical *arizonica* from other parts of the same formation and member. In fact, the round immature stages of the latter are often fully as large as the typical mature stage of this variety.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thick- ness	Locality	Length	Width	Thick- ness
All specimens from the Narrows, 2 mi. W. of Virgin City, 175 ft. down *	15	12	8	All specimens from the Narrows, 2 mi. W. of Virgin City, 175 ft. down *	13	11	7
	13	12	7		15	13	8
	14	12	7		12	11	7
	15	12	9		12	11	7
	15	13	7		14	13	8
	12	11	7				

* In this series all specimens are small. They resemble typical *Composita arizonica* in everything but size, and are like adults of that species in miniature.

Locality and horizon. Kaibab formation, β member (?), found in horizon 175 feet below top of formation at Narrows, 2 miles west of Virgin City, Utah.

Composita arizonica var.

(Plate 48, figures 17, 18)

Discussion. A very small, very rotund form of *Composita* which in other respects resembles typical *C. arizonica* has been found to be fairly common in certain zones near the base of the Toroweap formation, β member. These specimens are

in nearly every case about as thick as they are wide and not much longer, so their general appearance is that of small spheres. In most cases growth varices are numerous and strongly developed at the anterior margin.

Lack of median sinus and presence of strong lateral sinuses suggest the relationship to *C. arizonica*; however, the less pentagonal outline and the rotund shape, causing the tongue to extend downward rather than forward, may be sufficient criteria to justify establishment of a new species. Until more material is available for study, the writer prefers to consider it merely as a variety of *C. arizonica*.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thickness
All specimens from Grand Wash Canyon.....	9	7	6
	10.5	8	8
	9	7	7
	9	7	6
	....	9	9
	9	7	....

Locality and horizon. Common in the lower parts of the β member, Toroweap formation, at Grand Wash Canyon, Arizona, and Muddy Mountains, Nevada.

Composita sp.

(Plate 48, figure 19)

Discussion. A small form of *Composita* which has none of the diagnostic features of mature *C. arizonica*—i. e., flat, extended tongue without median sinus on ventral valve, pentagonal shape, pronounced median fold, and lateral sinuses on dorsal valve—occurs in abundance, but usually with poor preservation, in the Toroweap formation.

In this form the shell of the ventral valve is moderately convex, the dorsal valve less so. In outline it is round to elliptical. The general shape and size are so similar to those of young specimens of *C. arizonica* that the writer does not consider it advisable to describe this form as a new species on the basis of present material. On the other hand, in zones where this shell is found in abundance, no associated forms comparable to the mature *C. arizonica* are known, thus suggesting that adult specimens are being considered. If there is close relationship to any described species, further collecting will no doubt show this.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thick- ness	Locality	Length	Width	Thick- ness
Toroweap Valley.....	14	11	8	Muddy Mountains, Nev.	13	10	7
	15	12	8		12	9	6
	....	9	6		13	11	7
	8	7	4		13	11	....
					13	....	7

Locality and horizon. Common in middle part of massive limestone, β member, Toroweap formation, in Toroweap Valley and in Muddy Mountains, Nevada.

Composita subtilita (Hall)

(Plate 48, figure 20)

1852 *Terebratula subtilita*. Hall, *Rept. Stansbury's Exped. Great Salt Lake*, p. 409, pl. 4, figs. 1-2*b*.

(For full synonymy, see Girty, U. S. Geol. Surv. Bull. 544, 1915, p. 96. Some of these forms are now commonly regarded as separate species.)

Description. Shell medium-sized, outline suboval, width slightly less than length, greatest width anterior to middle; convexity of valves moderate.

Ventral valve convex with sharp curvature from umbo toward cardinal margin, but with gentle slope toward front and lateral margins. Narrow but usually well-defined mesial sinus or sulcus normally develops about mid length and extends to anterior margin with little change in size. Development of frontward-projecting tongue slight for this genus or not at all. Beak prominent, incurved about that of dorsal valve. Delthyrium concealed.

Dorsal valve convex, more curved transversely than longitudinally, with greatest convexity near umbo. Mesial fold broad and undefined, beginning near beak. Lateral slopes develop into shallow weakly defined lateral sinuses toward anterior margin. Beak tumid, incurved over delthyrium of the ventral valve.

Surface of valves marked by fine, close-set, concentric growth lines, some of which usually are prominent and stand out.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thickness
Fossil Mountain.....	23	22	14
	20	19	12
Shinumo Canyon.....	23	22	15
Kanab Canyon.....	28 *	23	11
	22	20	13
	20	17	....
	23	20	15
	20	17	14

* Abnormal length development.

Discussion. The normal great variability of this species and also the wide range of forms that have been referred to it by various palæontologists combine to make its status very difficult to ascertain. Specimens in the series from the Kaibab formation thought to represent this species show a size and shape almost exactly like that of Hall's types as illustrated by his figures. Since the Kaibab specimens also conform, as nearly as can be determined, to specimens from Texas which King refers to *Composita subtilita* and which are of comparable age, the writer feels little hesitation in applying the name.

In their recent discussion of the diagnostic features of certain *Compositas*, Dunbar and Condra point out that *C. ovata* and *C. subtilita* are very similar with "more or less intergradation in form" in the adult stage. Since the young of the latter are defined as thicker and more oval in outline and the species is apparently restricted to the Pennsylvanian period, however, it does not seem necessary to consider it further.

Some of the more trilobed specimens of *Composita* from the Hermosa formation of Colorado which Girty figured and referred to *C. subtilita* appear to be extremely

similar to the Kaibab specimens. They illustrate clearly all the distinctive characteristics, such as shape with greatest width just anterior to the middle, a well-defined, narrow sulcus in the anterior part of the ventral valve, moderately prominent lateral sinuses, and ill-defined anterior tongues. Also, they are of about the same size.

Comparisons. This form is greatly different from *C. arizonica*, the common species in the Kaibab formation. It differs in having a definite ventral median groove or sinus in the anterior half of the ventral valve and is much larger than the average of that species. It lacks a prominent anterior tongue, and the dorsal lateral sinuses are less prominent, giving it a totally different appearance.

Locality and horizon. Kaibab formation, β member; nowhere appears to be very common, but recorded from a number of localities. Specimens in the Grand Canyon collection from Fossil Mountain in Grand Canyon, and in the U. S. Geological Survey collection from Shinumo and Kanab Canyons, have been examined by the writer. Probably some of the various forms of *Composita* shown in the faunal lists as compiled under *C. arizonica* refer to this species.

Dielasma phosphoriensis C. Branson

(Plate 48, figures 21, 22)

1930 *Dielasma phosphoriensis*. C. Branson, *Paleontology and stratigraphy of the Phosphoria formation*, Univ. Missouri Studies, vol. 5, no. 2, pp. 34-35, pl. 2, figs. 21-25.

Top limestone member, Wind River and Owl Creek Mountains, Wyoming; *Hustedia* member, Owl Creek Mountains, Wyoming.

Description. Shell spatulate, small to medium-sized, smooth. Width about three-fourths as great as length. Greatest width near mid length. Posterior end pointed and tapering; anterior contracted and strongly rounded.

Ventral valve has convex longitudinal profile with greatest curvature near the beak, which is incurved over the dorsal beak. Foramen circular, located in the termination of the beak. A broad, shallow sinus is developed near the anterior margin but not always apparent back from the margin.

Dorsal valve subcircular in outline, strongly bent in transverse profile but only gently arched in longitudinal profile. Convex sides slope steeply away from rounded median fold near anterior margin. Beak small, largely hidden under extended ventral valve.

Measurements. Typical specimens (in millimeters):

Locality	Length	Width	Thick- ness	Locality	Length	Width	Thick- ness
Fossil Mountain.....	26	18	11	Narrows.....	....	15	....
Kanab Canyon	20	12	8		....	15	....
	....	11	6	Toroweap.....	16	12	7
	....	12	6		....	15	9
	....	11	....		....	13	8

Discussion. The most apparent distinguishing characteristics of this species are (1) greatest width near mid length and not anterior to it, and (2) narrow rounded anterior margin, not wide and straight, nor two-lobed. By these characteristics as

well as others it may readily be distinguished from all other Permian species except *Dielasma? scutulatum*, which, however, differs in having a shallow dorsal valve with curvature less across than lengthwise. Also both fold and sinus apparently are much less developed.

The Kaibab form disagrees with Branson's description of *D. phosphoriensis* in having larger size, but appears to be so similar in all other respects that it does not seem desirable to consider it even a variety.

A specimen of *Dielasma* from south of St. George, Utah, presumably from the Kaibab formation, has been referred to *D. bovidens* by White (1877), but judging from his figures and description it represents *D. phosphoriensis*.

Locality and horizon. Found in β member of Kaibab formation at Fossil Mountain, Grand Canyon, 3 specimens; in Kanab Canyon, 4 specimens, U. S. Geol. Surv. coll.; 2.5 miles west of Virgin City in Narrows, 2 specimens, U. S. Geol. Surv. coll. Common in limestone bed of α member, Kaibab formation, at head of Toroweap Valley.

In published faunal lists representatives of this genus have been referred to as *Dielasma* sp., Kaibab α and β members, northwestern Arizona and southwestern Utah (73), and as *D. bovidens*, Kaibab β , 3 miles south of Jacob's Lake (77). (Numbers in parentheses refer to bibliography.)

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Section of Middle Permian strata in Toroweap Valley, Arizona

M = Moenkopi formation	T = Toroweap formation	H = Hermit shale
K = Kaibab formation	C = Coconino sandstone	



a



b



c



d

a. Section of Kaibab formation at Grand Falls of the Little Colorado
b. Section of Toroweap and Kaibab formations along Hurricane Ledge near Mount Trumbull
c. Northeasternmost known exposure of Kaibab formation, Black Box of San Rafael River
d. Westernmost known exposure of Toroweap and Kaibab formations, Spring Mountains, Nevada

M = Moenkopi K = Kaibab T = Toroweap H = Hermit
C = Coconino CM = Cedar Mesa



a

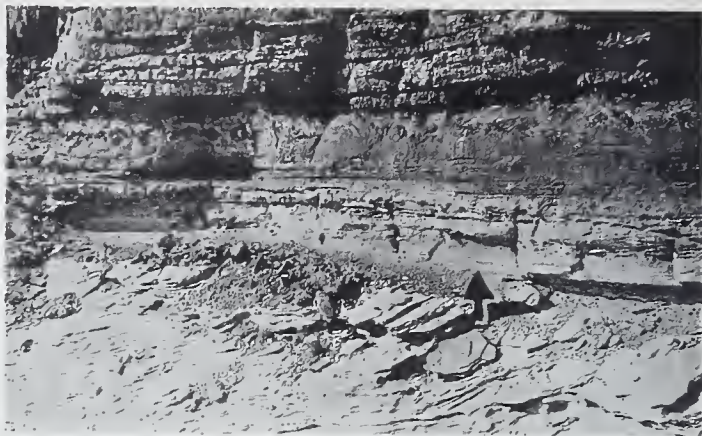


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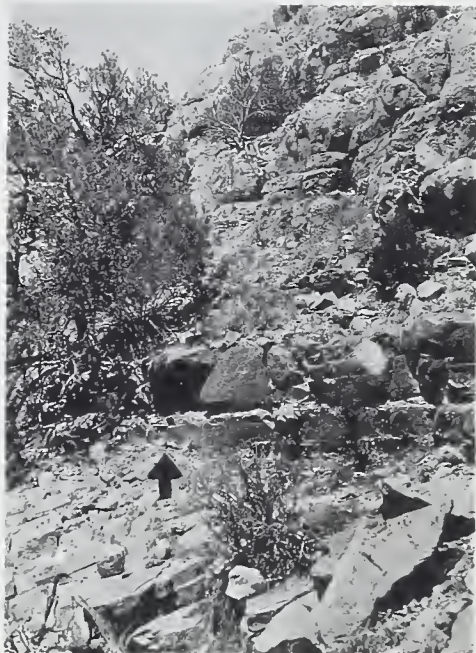


c

- a.* Kaibab formation, 3 miles southwest of Winslow, Arizona
b. Kaibab formation in Chevelon Canyon, Arizona
c. Kaibab formation in Little Colorado Canyon near Cameron
M = Moenkopi K = Kaibab C = Coconino



a



b



c



d

- a.* Toroweap-Coconino contact, Toroweap Valley
- b.* Toroweap-Coconino contact, Aubrey Cliffs, northwest of Seligman
- c.* Toroweap-Coconino contact, Point Imperial, Grand Canyon
- d.* Toroweap-Coconino contact, Sycamore Canyon



a



b



c



d

- a.* Red beds of Toroweap α member, below Grandeur Point, Grand Canyon
- b.* Gnarly structure developed in red beds, Toroweap α , below Grandeur Point, Grand Canyon
- c.* Gnarly structure developed in cross-laminated sandstone, Toroweap formation, Oak Creek Canyon
- d.* Gnarly structure developed in thin quartzitic beds, Toroweap formation, Little Colorado Canyon



a



b

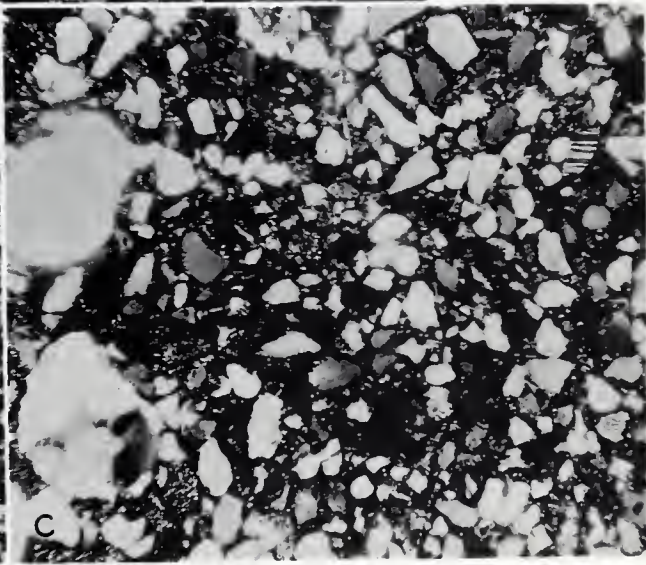
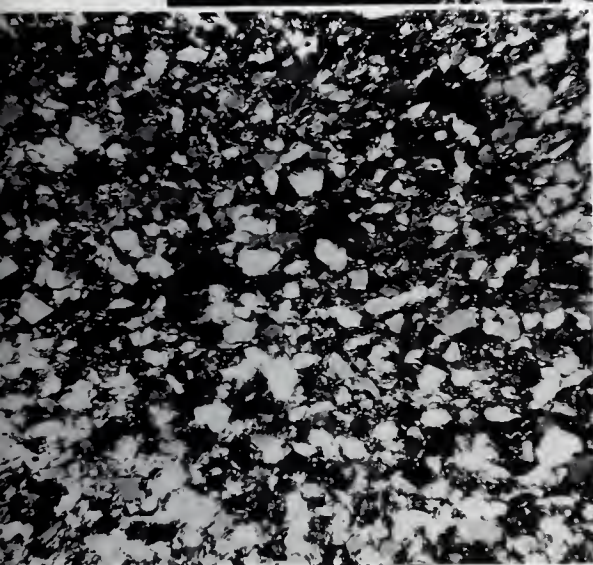
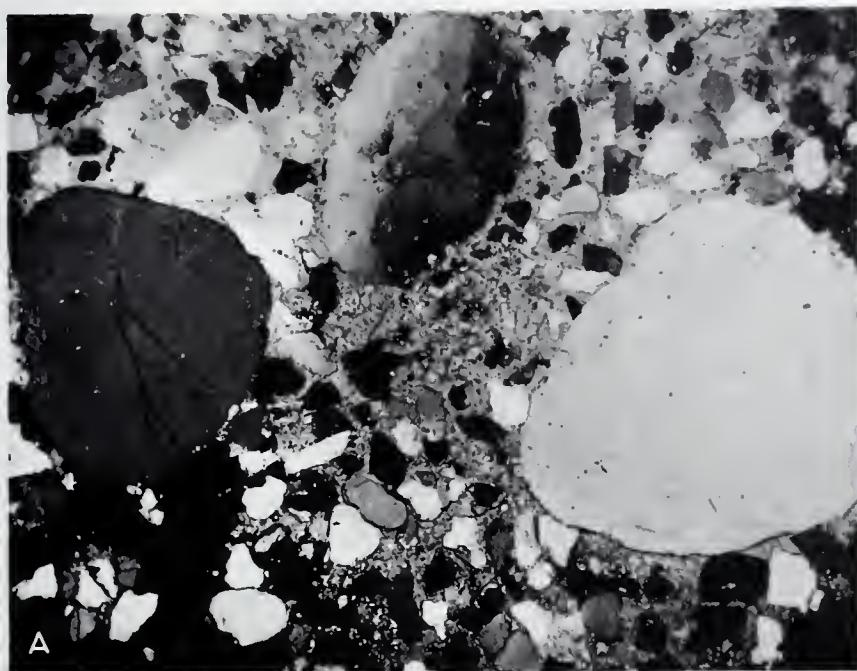


c



d

- a.* Sun cracks in chemical limestone, Toroweap α , Parashant Canyon
- b.* Molds of pelecypods in limestone of Toroweap α , Fossil Mountain, Grand Canyon
- c.* Travertine in red beds, Toroweap α , Fossil Mountain, Grand Canyon
- d.* Gnarly-bedded sandstone of Toroweap α , Straight Canyon



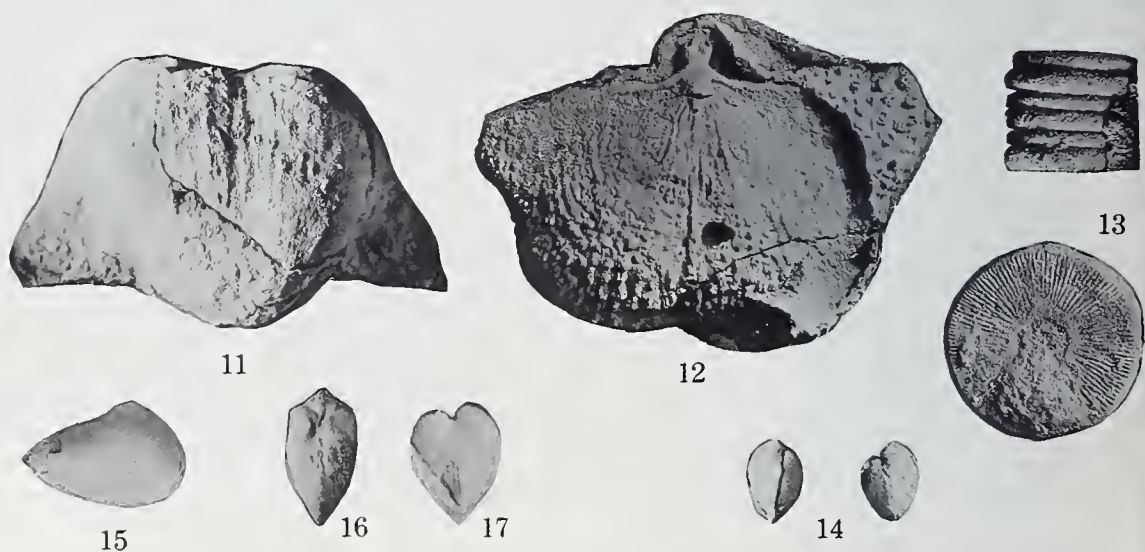
a. Photomicrograph of white, cross-laminated sandstone ($\times 40$), Toroweap eastern phase

b. Photomicrograph of green shale ($\times 40$), Toroweap γ , facies 2

c. Photomicrograph of basal red sandstone ($\times 40$), Toroweap γ , facies 2

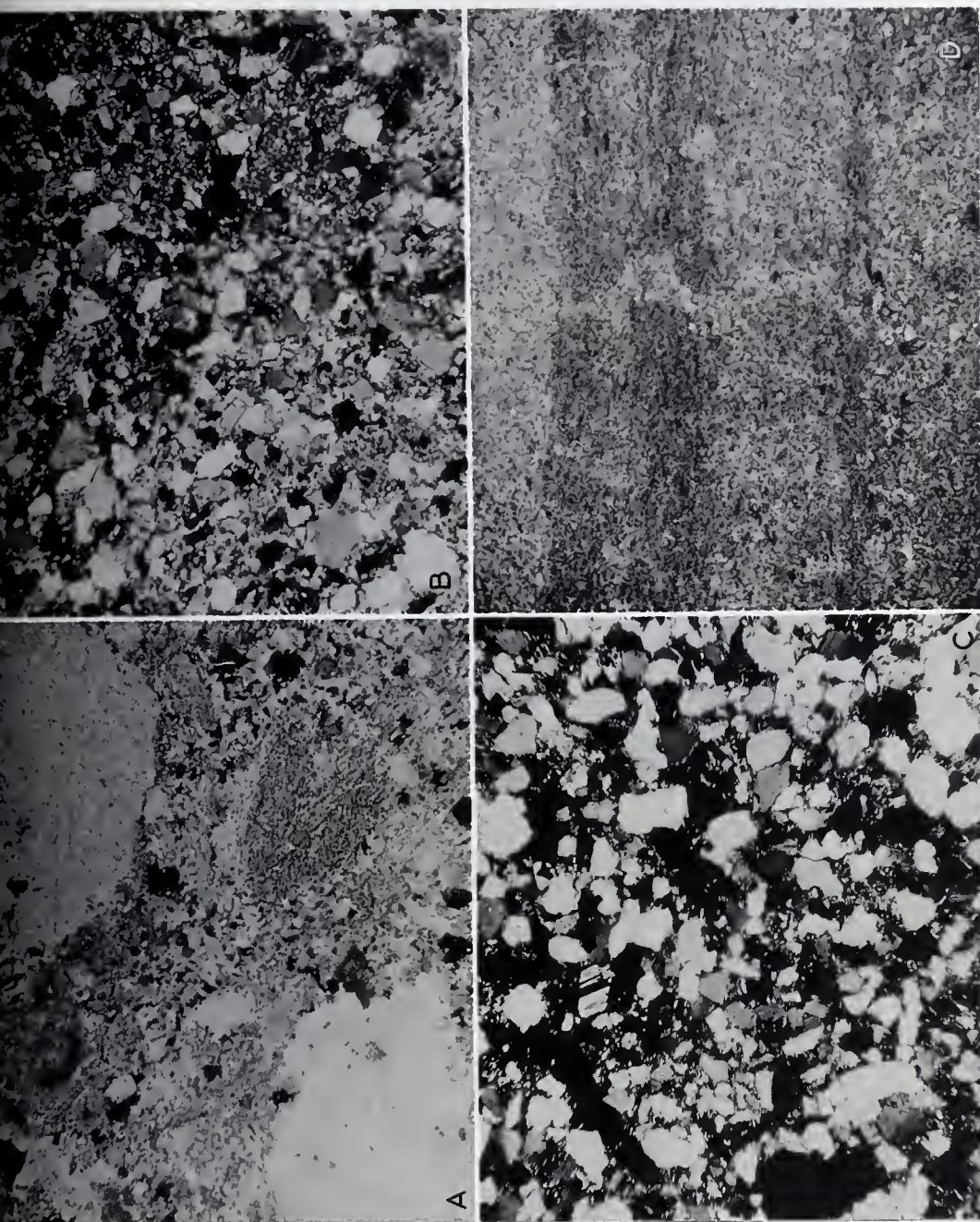


Fauna of Toroweap formation, facies 2 of β member. 1, *Productus ivesi*. 2, *Schizodus*. 3, *Euphemus*? 4, *Leda*. 5, *Nucula*. 6, *Bellerophon*. 7, *Pleurophorus*. 8, *Bucanopsis*. 9, *Astartella*. 10, crinoid.



Fauna of Toroweap formation, facies 1 of β member. 11, 12, *Productus ivesi*. 13, crinoid. 14, *Composita*.

Fauna of Toroweap formation, facies 1 and 2 of α member. 15, 16, 17, *Schizodus*?



a. Photomicrograph of coarse-grained marine limestone ($\times 40$), Toroweap β , facies 1
b. Photomicrograph of sandy, near-shore limestone ($\times 40$), Toroweap β , facies 2
c. Photomicrograph of typical red bed ($\times 40$), Toroweap α , facies 2
d. Photomicrograph of banded chemical limestone ($\times 40$), Toroweap α , facies 1



a



b

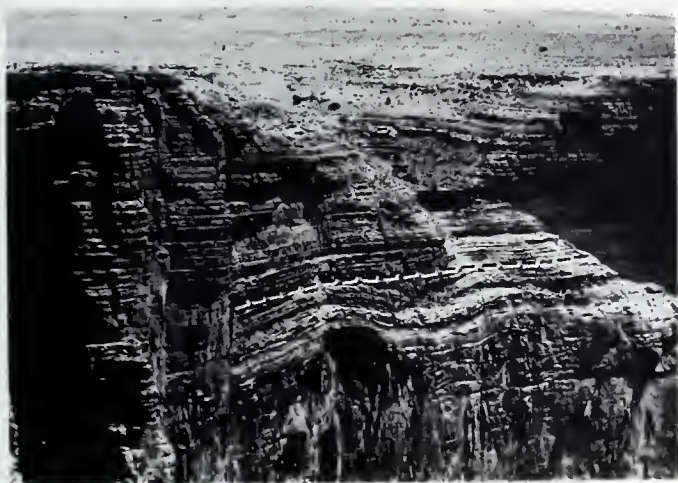


c

- a.* Conglomerate at base of Kaibab formation, Badger Canyon
- b.* Kaibab-Toroweap unconformity, Hilltop at Havasu Canyon
- c.* Conglomerate at base of Kaibab formation, Fossil Mountain



a



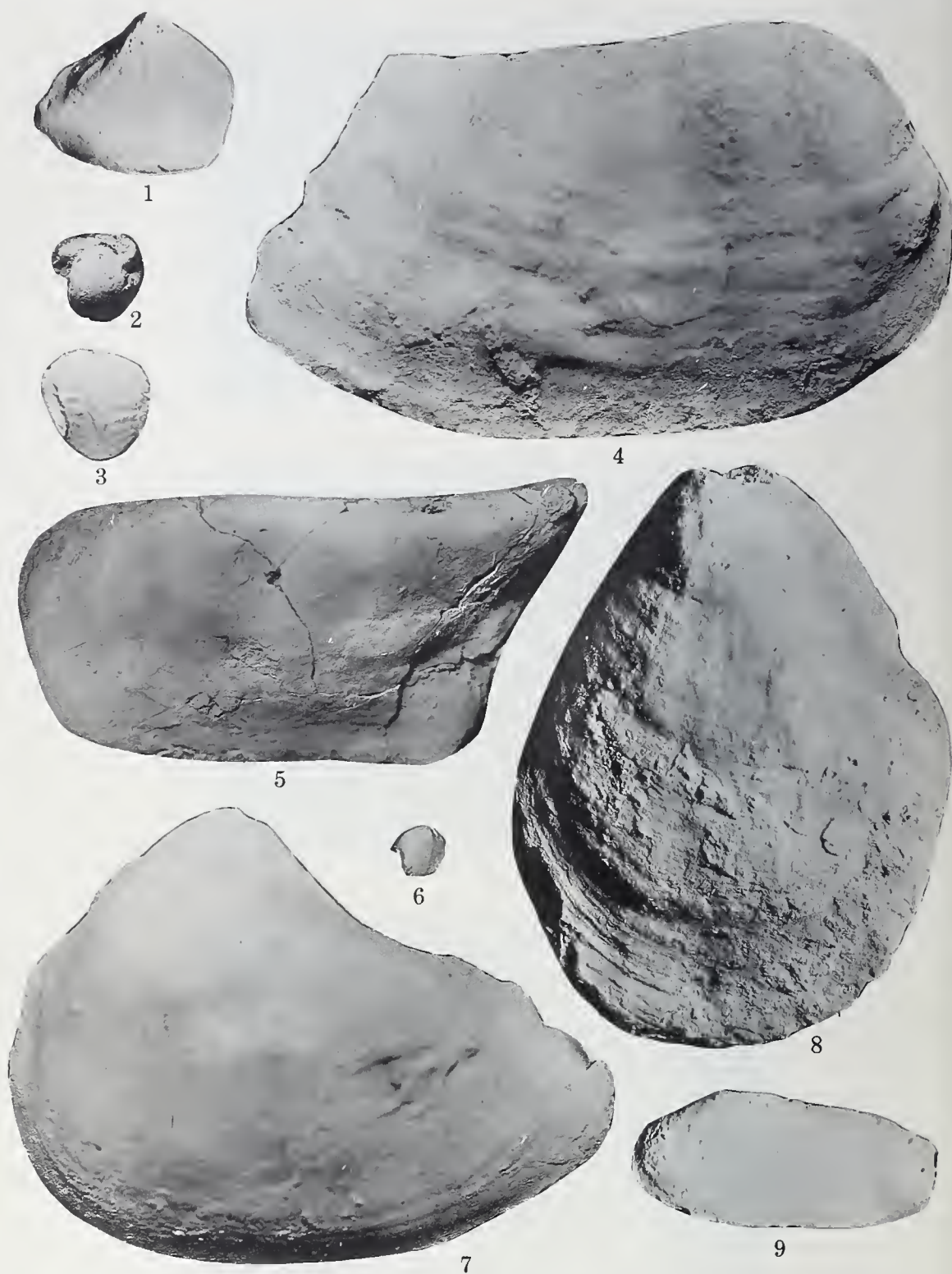
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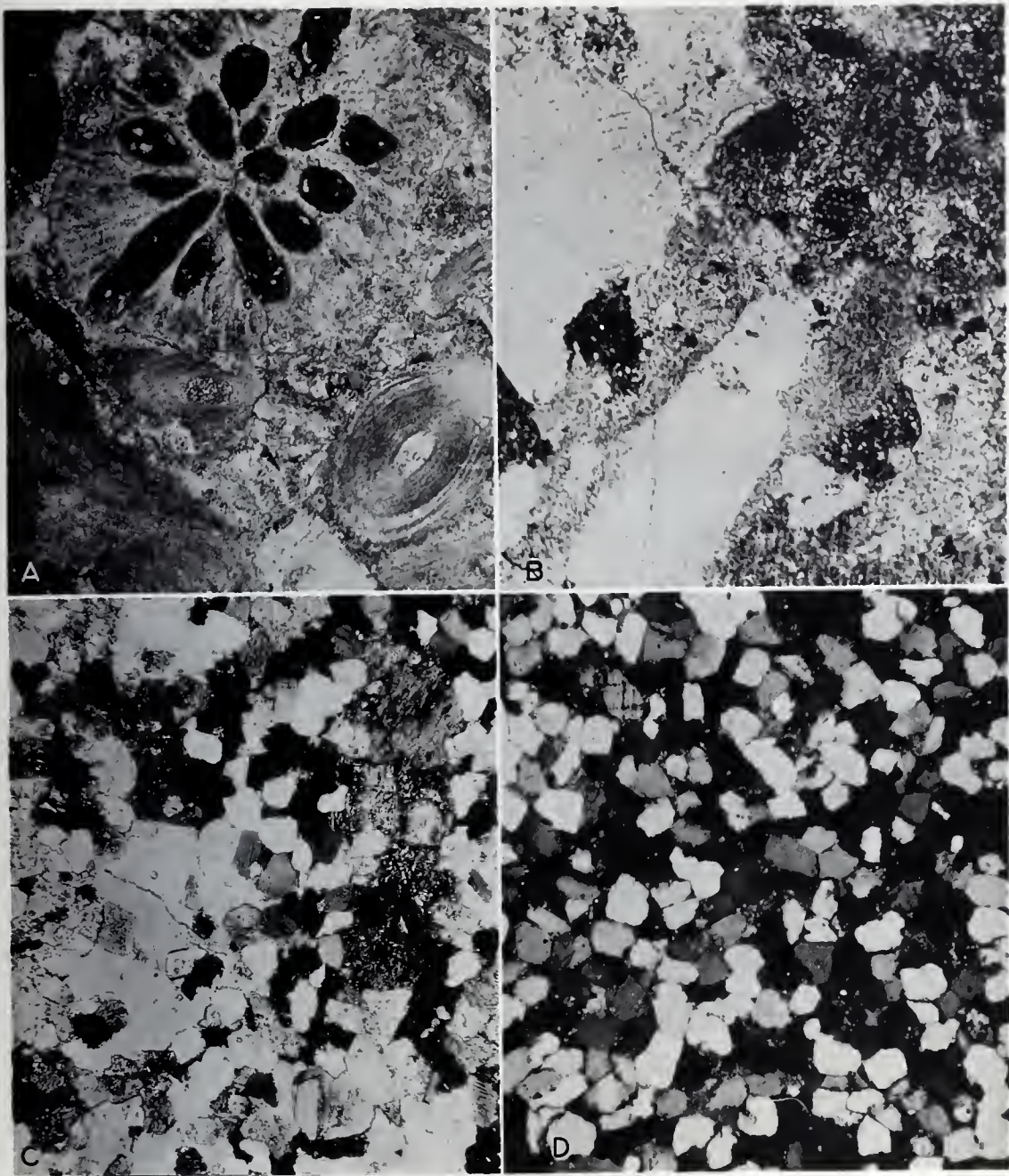
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a. Unconformity between Kaibab formation and Cedar Mesa (?) sandstone, Black Box Canyon, Utah

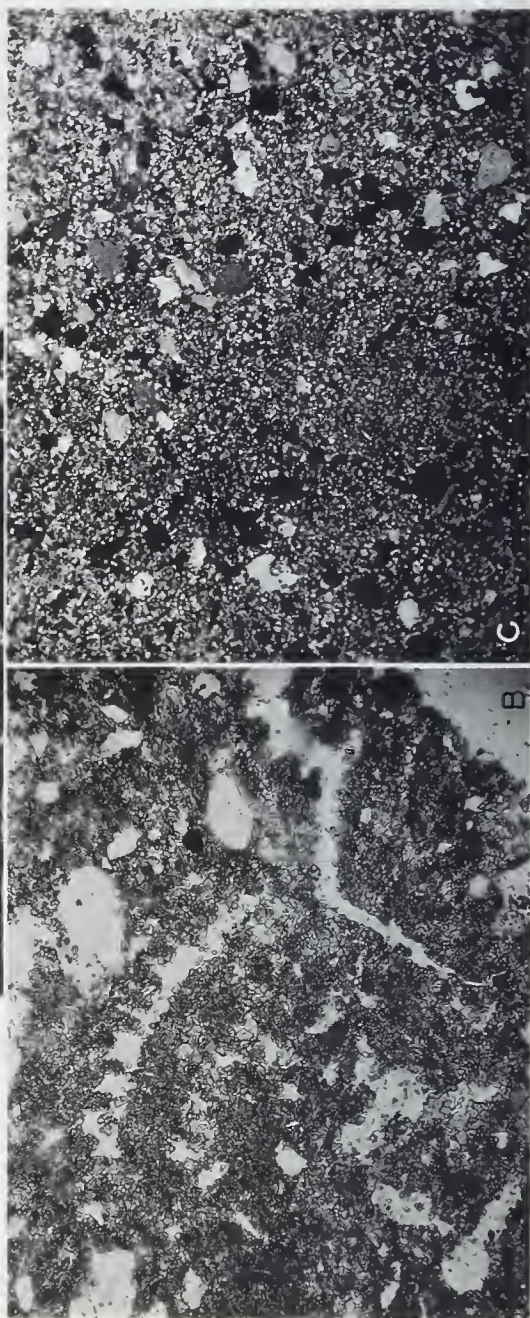
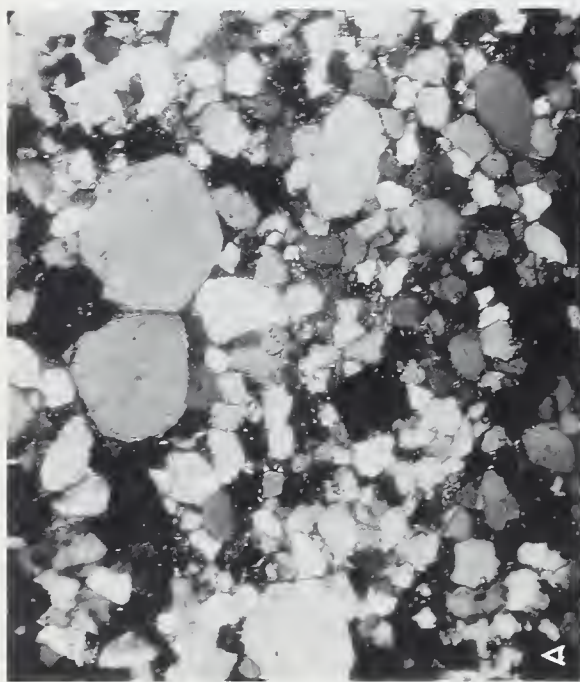
b, c. Kaibab-Toroweap unconformity at Little Colorado Canyon (*b*) and in Badger Canyon (*c*). (*b*, photograph by D. Rockefeller.)



Fauna of Kaibab formation, facies 1 of γ member. 1, *Schizodus*. 2, *Euphemus*? 3, *Euphemus*. 4, *Allorisma* ($\times \frac{2}{3}$). 5, *Myalina* ($\times \frac{2}{3}$). 6, *Bucanopsis*. 7, *Schizodus*? 8, *Pseudomonotis* ($\times \frac{2}{3}$). 9, *Solenomya*.



- a.* Photomicrograph of fossiliferous marine limestone ($\times 40$), Kaibab β , facies 1
b. Photomicrograph of coarse-grained marine limestone ($\times 40$), Kaibab β , facies 1
c. Photomicrograph of sandy limestone ($\times 40$), Kaibab β , facies 2
d. Photomicrograph of brackish-water sandstone ($\times 40$), Kaibab β , facies 3



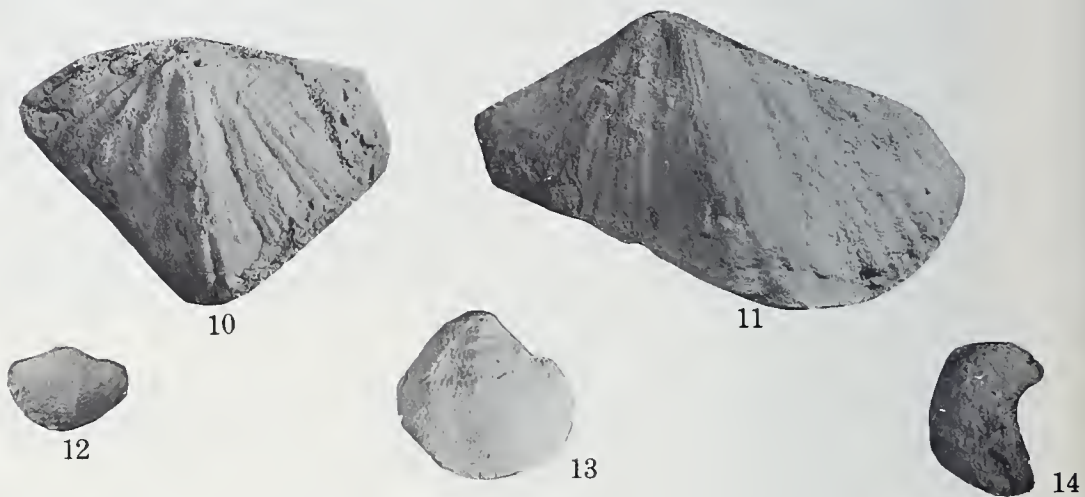
- a.* Photomicrograph of calcareous sandstone of Kaibab β , facies 2 ($\times 40$)
- b.* Photomicrograph of dolomitic limestone of Kaibab β , facies 4 ($\times 40$)
- c.* Photomicrograph of sandy limestone of Kaibab β , facies 5 ($\times 40$)



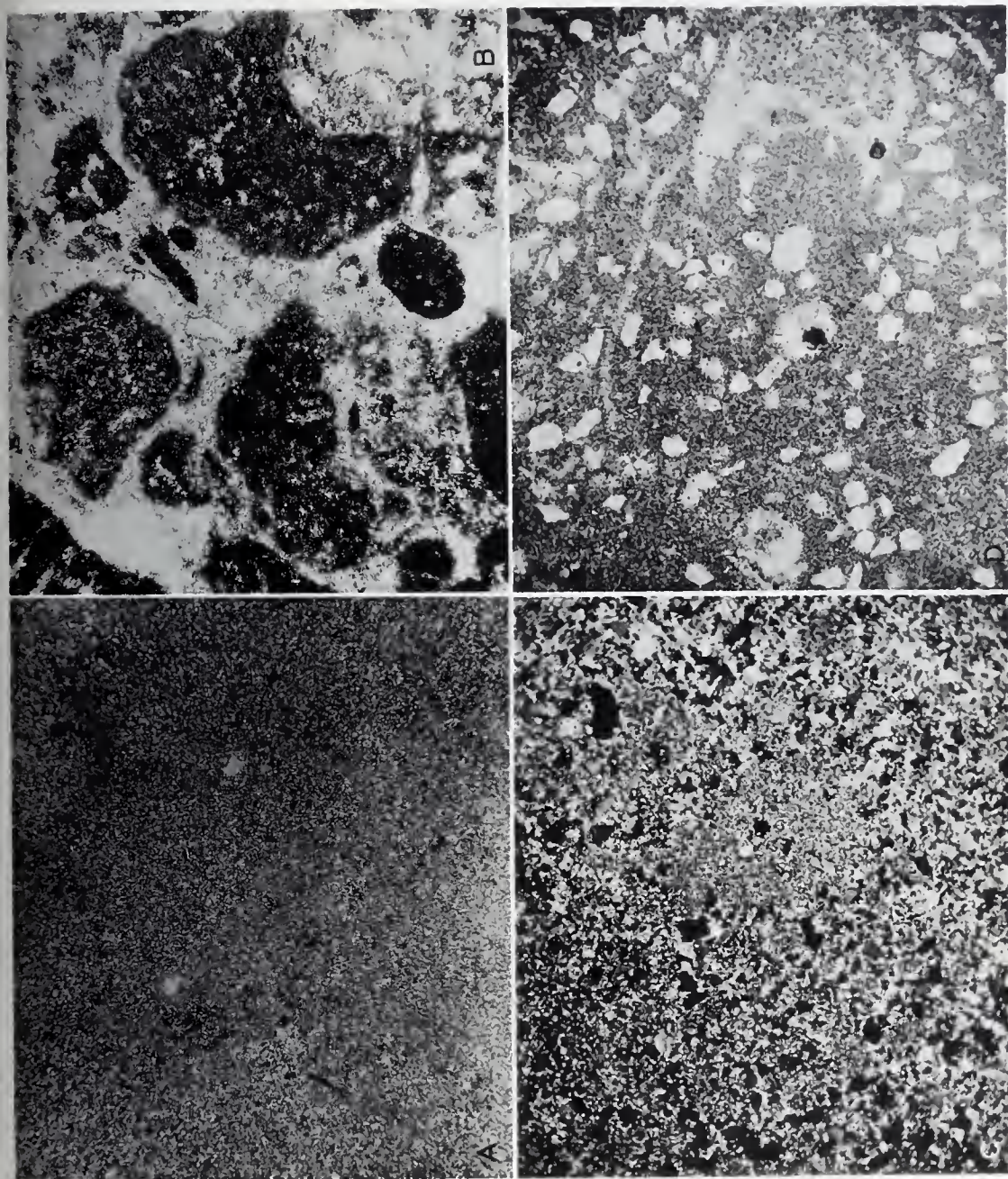
Fauna of Kaibab formation, facies 3 of β member. 1, *Soleniscus*? 2, *Myalina*? 3, *Euphemus*? 4, *Solenomya*. 5, *Astartella*. 6, *Pleurophorus*. 7, *Edmondia*. 8, *Aviculopecten*. 9, *Schizodus*. 10, *Solenomya*. 11, *Plagioglypta*. 12, *Dentalium*. 13, *Pteria*. 14, *Deltodus*. 15, *Leda*.



Fauna of Kaibab formation, facies 4 of β member. 1, *Deltopecten*. 2, *Schizodus*. 3, *Myalina*. 4, *Pugnoides*. 5, *Leda*. 6, *Hustedia*. 7, 8, *Archæocidaris*. 9, *Pleurophorus*.



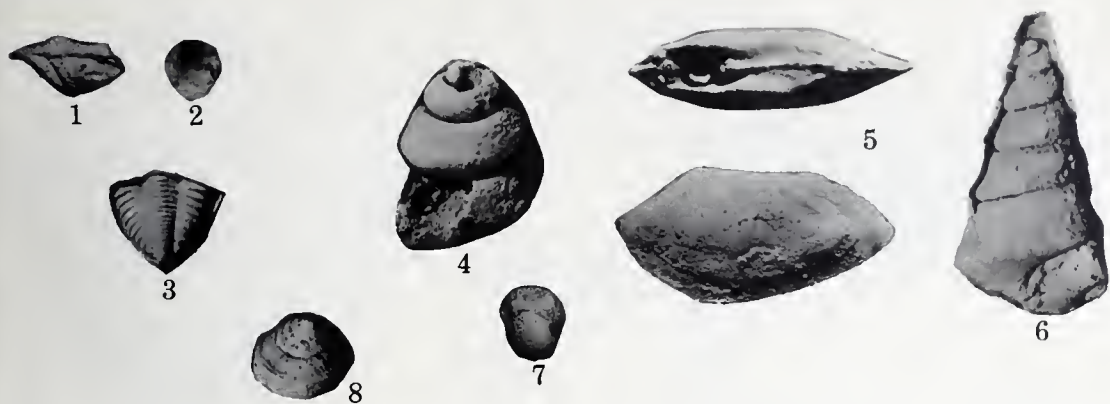
Fauna of Kaibab formation, facies 5 of β member. 10, 11, *Spirifer pseudocameratus*. 12, *Squamularia*. 13, *Waagenoconcha*. 14, *Pustula nevadensis*.



a. Photomicrograph of chemical limestone ($\times 40$), Kaibab α , facies 2
b. Photomicrograph of magnesial limestone ($\times 40$) with mollusks, Kaibab α , facies 2
c. Photomicrograph of magnesial limestone ($\times 40$) with mollusks, Kaibab α , facies 4
d. Photomicrograph of magnesial limestone ($\times 40$) with mollusks, Kaibab α , facies 3



Fauna of Kaibab formation, facies 2 of α member. 1, *Deltopecten*. 2, *Chonetes*. 3, *Pleurotomaria*. 4, *Euomphalus*. 5, *Productus bassi*. 6, *Schizodus*. 7, *Pleurotomaria*. 8, phygidium of *Ditomopyge*. 9, *Plagioglypta*. 10, *Euphemus* ? 11, *Pleurophorus*. 12, *Alorisma*.



Fauna of Kaibab formation, facies 3 of α member (near Flagstaff). 1, 2, 3, cheek, glabella, and pygidium of *Ditomopyge*. 4, gastropod. 5, pelecypod. 6, *Pleurotomaria*. 7, *Euphemus*? 8, gastropod.



Fauna of Kaibab formation, facies 1 of α member. 9, *Composita*. 10, *Diclasma*. 11, *Euphemus*? 12, *Euomphalus*.



Fauna of Kaibab formation, facies 3 of α member (at Padre Canyon). 1, *Allorisma*. 2, *Chonetes*. 3, *Leda*. 4, *Bellerophon*. 5, *Astartella*. 6, *Euomphalus*. 7, *Pleurophorus*. 8, *Nucula*. 9, *Orthoceras*. 10, *Marginifera*. 11, *Euphemus*. 12, *Bucanopsis*. 13, *Plagioglypta*. 14, *Naticopsis*. 15, *Schizodus*. 16, *Productus bassi*.



Fauna of Kaibab formation, facies 4 of α member. 1, *Plagioglypta*. 2, *Schizodus*. 3, *Astartella*. 4, 5, 6, gastropods. 7, *Bellerophon*. 8, *Naticopsis*. 9, *Nucula*. 10, *Bucanopsis*. 11, *Bellerophon*. 12, *Euomphalus*. 13, gastropod.



a



b



c

- a.* Moenkopi-Kaibab unconformity near Hance Trail, Grand Canyon
b. Even contact between Kaibab and Moenkopi formations, Citadel Sink
c. Conglomerate of limestone boulders, base of Moenkopi formation, Rimey Jim's, south of Cameron



a



b



c

- a.* Moenkopi-Kaibab unconformity south of The Peaks, Circle Cliffs, Utah
- b.* Basal conglomerate of Moenkopi formation, near Lees Ferry, Arizona
- c.* Basal conglomerate of Moenkopi formation, Black Box Canyon, San Rafael, Utah



a



b

a. Spherical concretion, type 1 chert with sponge center, Kaibab β , Hermit Trail, Grand Canyon. (Photograph by N. Dodge.)

b. Nodular concretions, type 2 chert, Kaibab β , Hermit Trail, Grand Canyon. (Photograph by N. Dodge.)



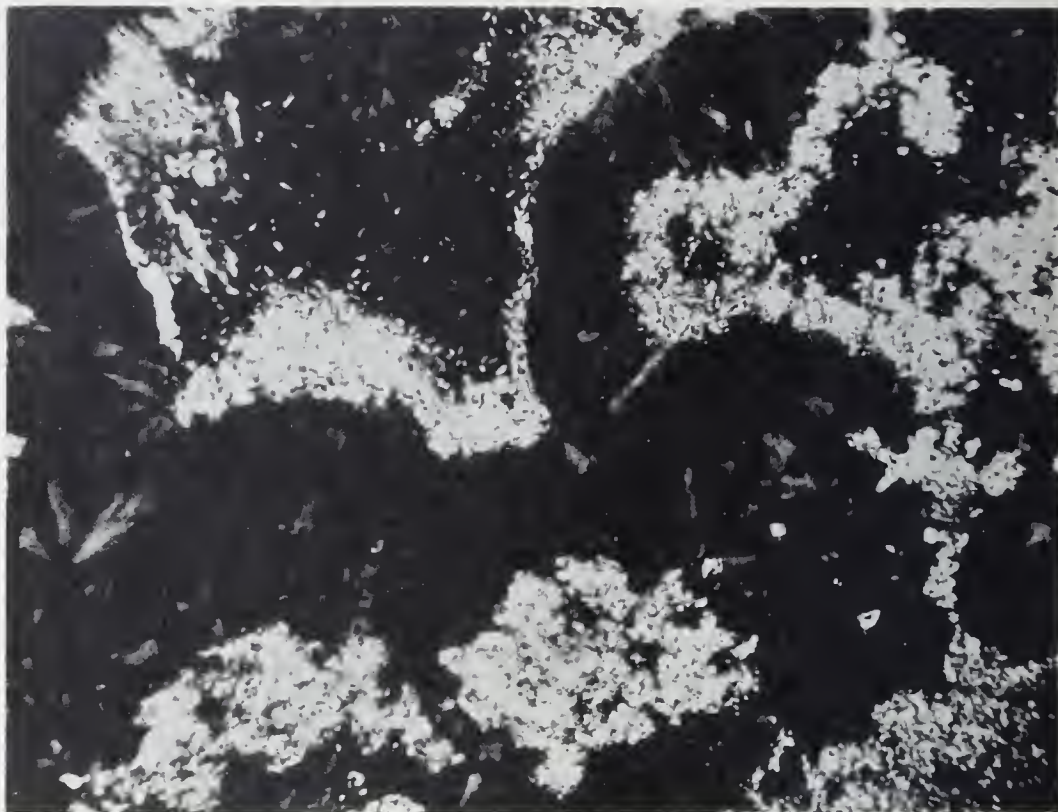
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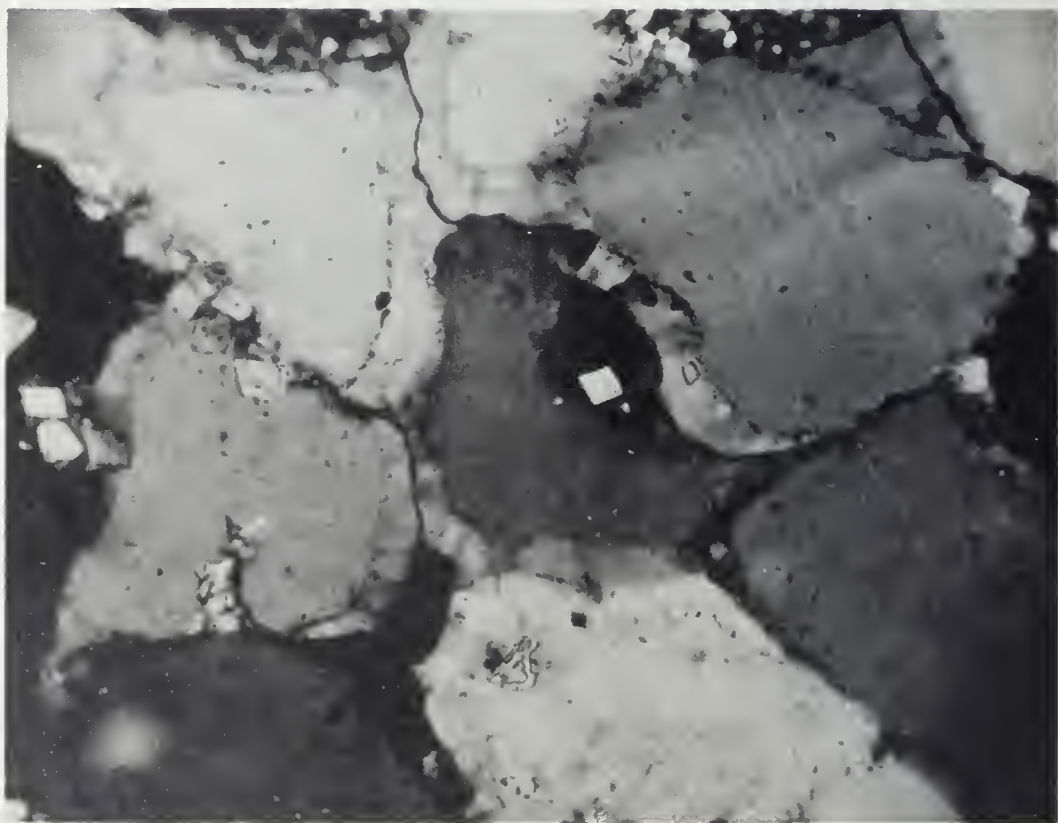
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a. Molds of erinoid joints on chert surface, silicified joints in limestone, Kaibab β , Hermit Trail, Grand Canyon. (Photograph by N. Dodge.)

b. *Productus* shell which apparently limited growth of concretion, Kaibab β , Hermit Trail, Grand Canyon. (Photograph by N. Dodge.)



a



b

a. Photomicrograph of type 1 chert showing chalcedony sponge structure with carbonate-filled interstices, Kaibab β from Hermit Trail ($\times 300$)

b. Photomicrograph of quartzitic concretion (type 3) showing secondary enlargement of quartz, and dolomite rhombs, Kaibab β from Hermit Trail ($\times 300$)



a



b



c

a. Thickening of sandy limestone between chert beds, Kaibab β , Kaibab Trail, Grand Canyon

b. Alternating beds of chert (type 4) and sandy limestone, Kaibab β , Kaibab Trail, Grand Canyon

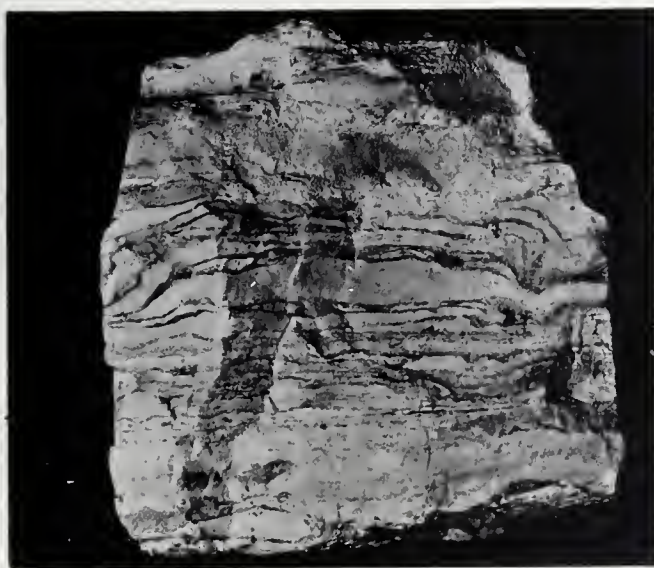
c. Quartzitic concretions and bands (type 3), Kaibab β , Hermit Trail, Grand Canyon



Photomicrograph of bedded chert, type 4, showing dolomite rhombs and finer carbonates scattered through silica (black), Kaibab β from Kaibab Trail ($\times 600$)



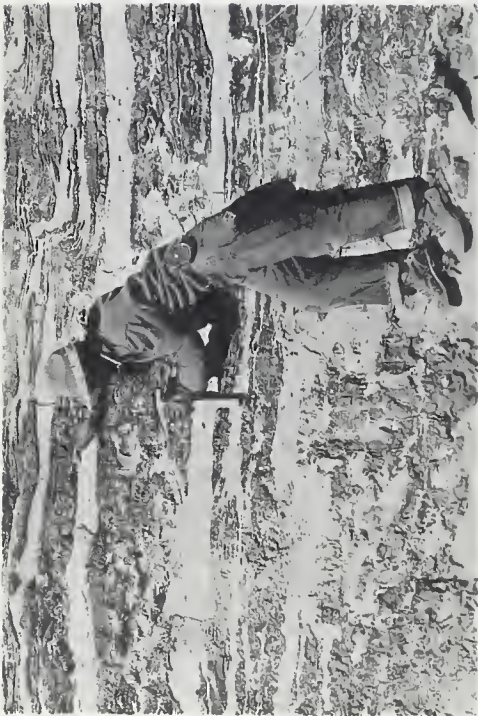
a



b

a. Blue chert of type 5 in yellow sandstone, Kaibab β , Hermit Trail, Grand Canyon. (Photograph by N. Dodge.)

b. Banded chert of type 9, Kaibab α , Hermit Trail, Grand Canyon. (Photograph by N. Dodge.)



a



b



c



d

a. Banded chert in α member of Kaibab, Shivwits Plateau
b. Concentric layer type of chert, top of β member of Kaibab, Shivwits Plateau
c. Large spherical concretion probably of type 1, Kaibab β , Shivwits Plateau
d. Irregular chert masses, Kaibab β , Goodsprings, Nevada



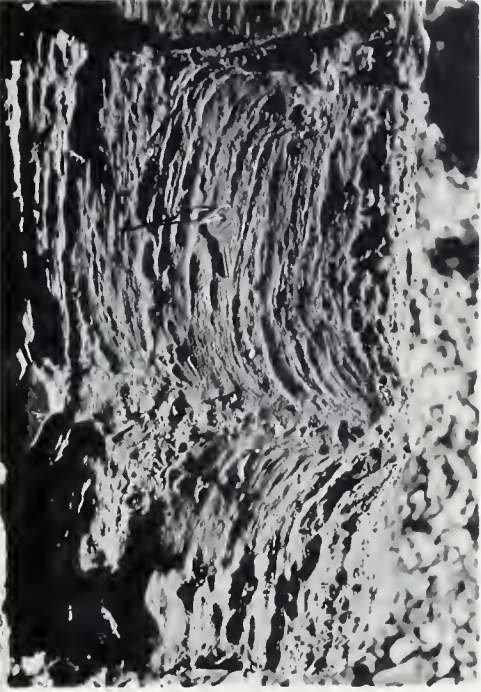
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b

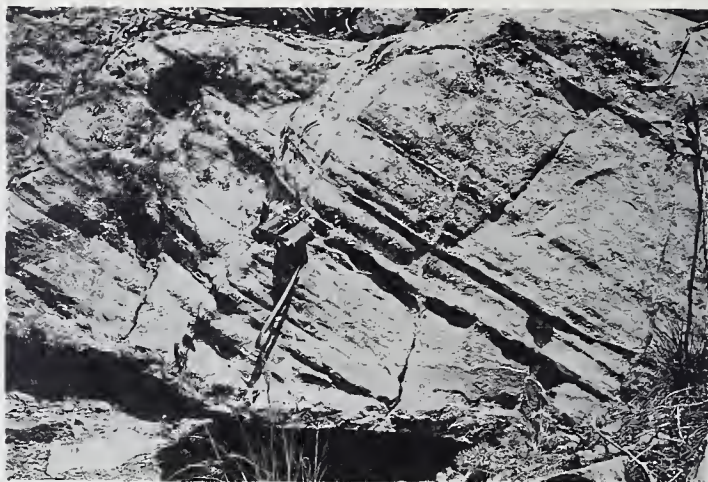


c



d

- a. Repeated cross-laminations in calcareous sandstone, top Kaibab β , Badger Canyon
- b. Typical cross-lamination in calcareous sandstone, top Kaibab β , Little Colorado Canyon
- c. Typical cross-lamination in calcareous sandstone, top Kaibab β , Badger Canyon
- d. Slumping of unconsolidated beds, calcareous sandstone, top Kaibab β , Badger Canyon



a



b



c

- a.* Tongue of white sandstone in Toroweap α red beds, Kaibab Trail
b. Eastern phase Toroweap sandstones above Coconino, Lee Canyon
c. Eastern phase Toroweap sandstones (?) below Kaibab, Walnut Canyon



a



b

- a.* Coconino-like sandstone in α member Kaibab, Long Valley, Arizona
b. Mollusk "pocket" in magnesian limestone of Kaibab α , facies 4, Rimey Jim's, south of Cameron, Arizona



b

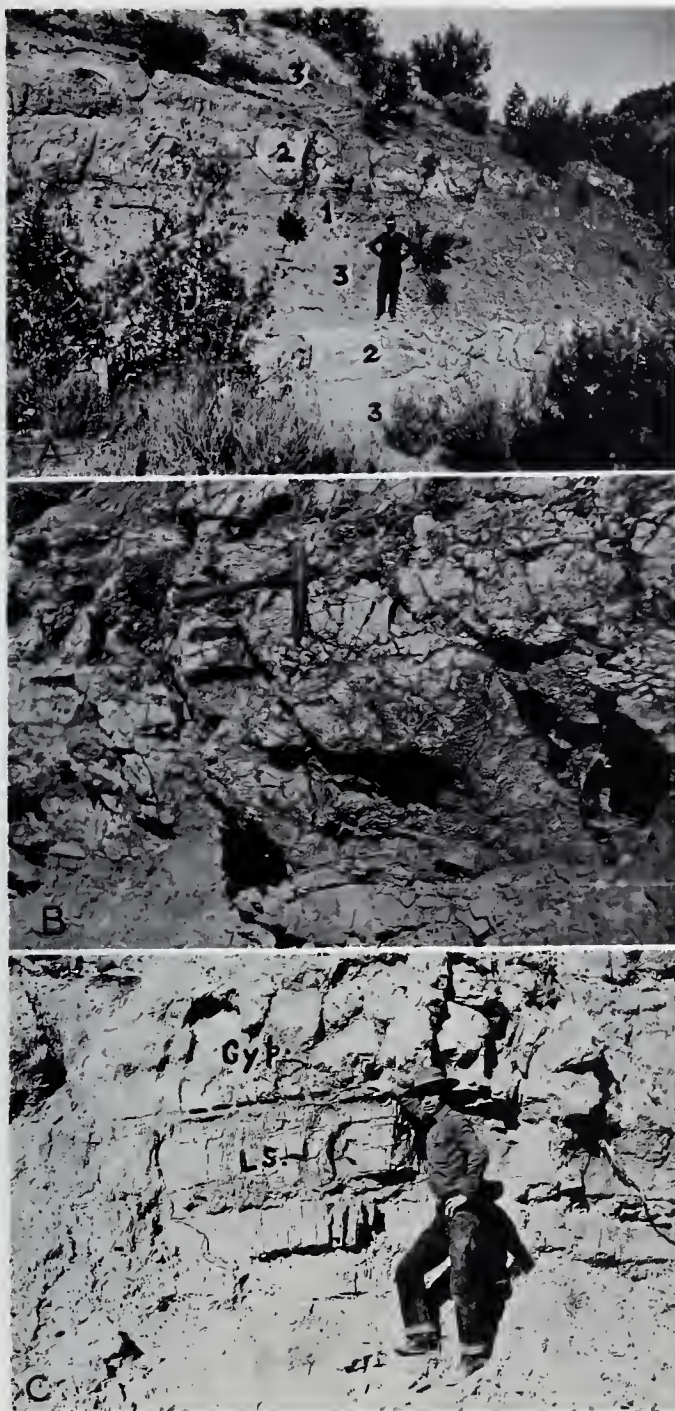


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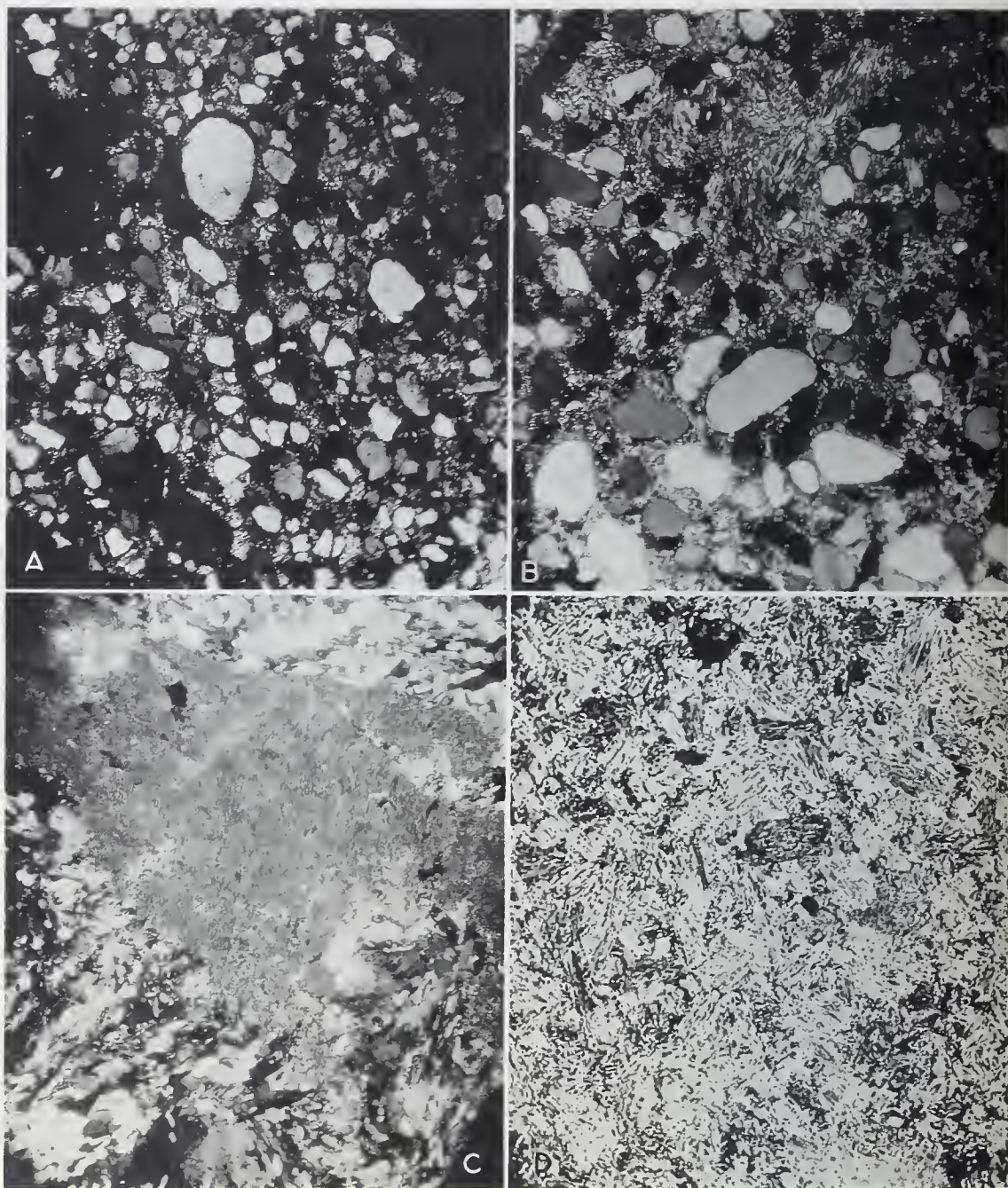


a

Examples of scour-and-fill cross-lamination in eastern portion of Torowcap γ , Tanner Trail, Grand Canyon



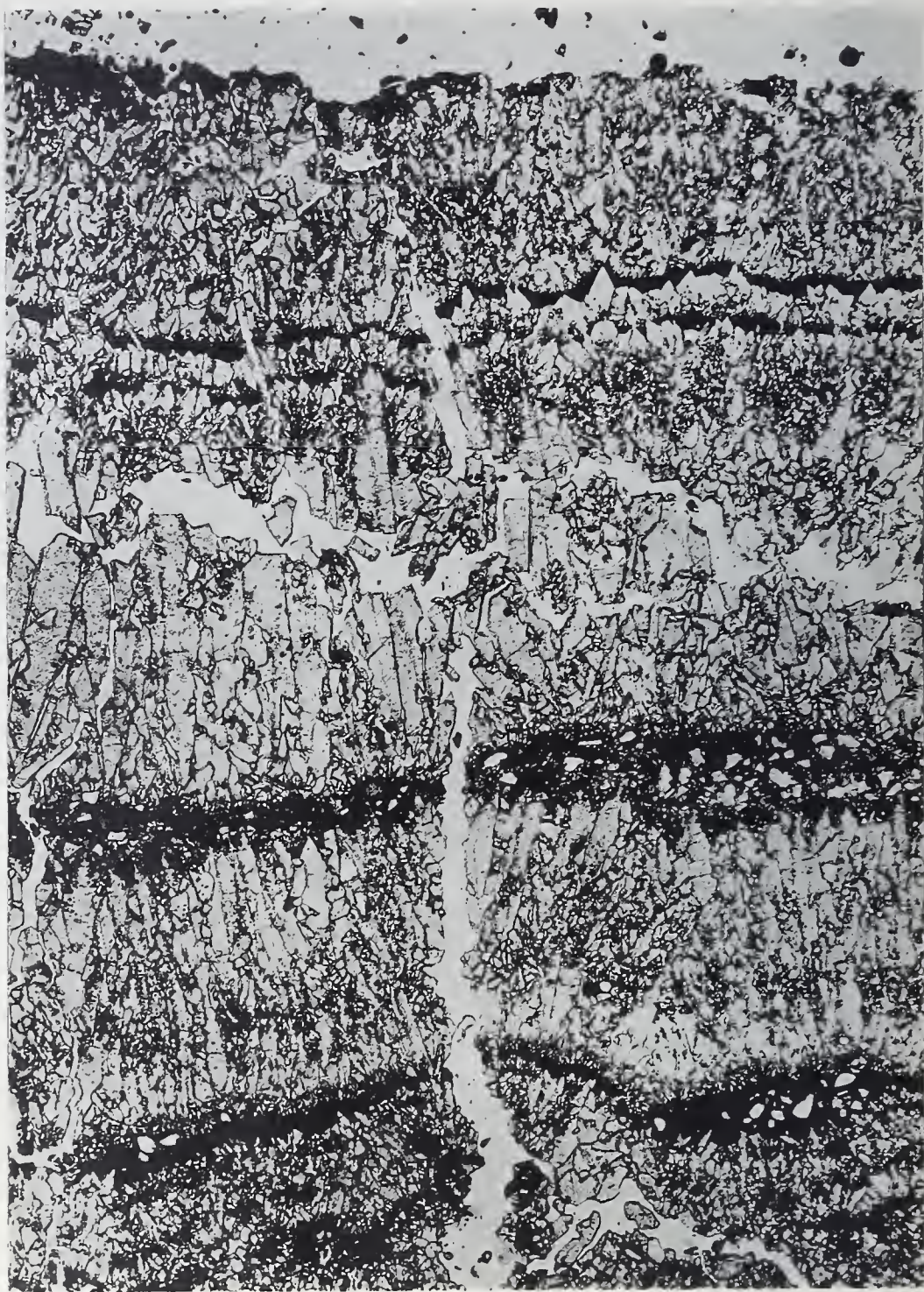
a. Limestone (1), gypsum (2), red bed (3) sequence, north of Wolf Hole, Arizona
b. Impure gypsum in red beds, Hilltop at Havasu Canyon, Arizona
c. Pure gypsum in contact with chemical limestone, north of Wolf Hole, Arizona



- a. Photomicrograph of red bed with gyp cement from Hilltop, Toroweap α , facies 1
b. Photomicrograph of impure gypsum from Hilltop, Toroweap α , facies 1
c. Photomicrograph of limestone-gypsum mixture from Hilltop, Toroweap α , facies 1
d. Photomicrograph of pure gypsum from north of Wolf Hole, Toroweap α , facies 1



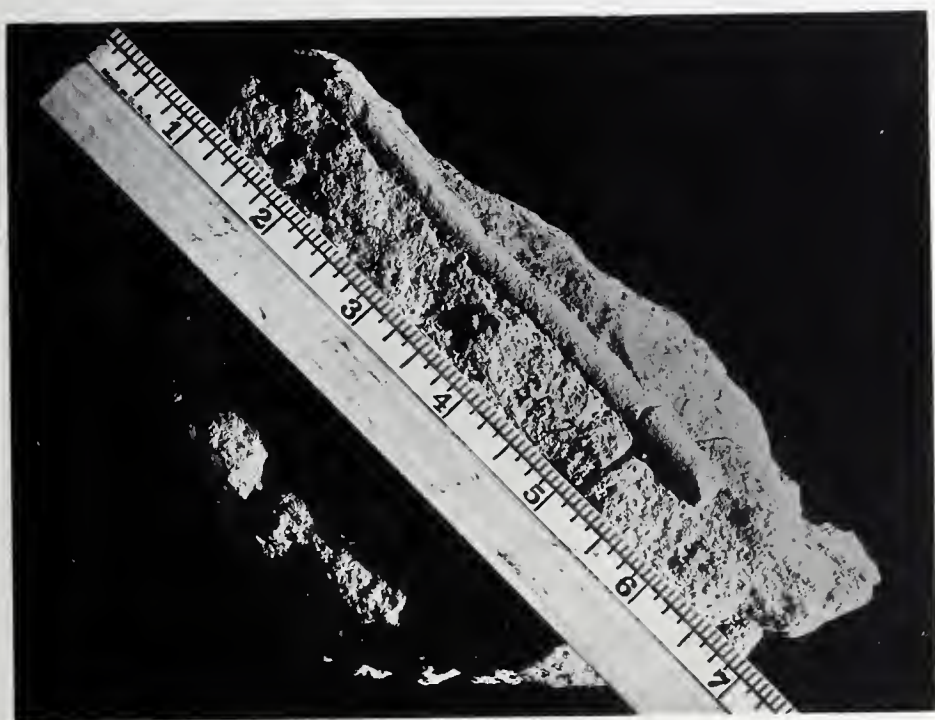
Intraformational conglomerate in red beds of Toroweap α , Hermit Trail, Grand Canyon.
(Photograph by G. Grant. Courtesy of National Park Service.)



Photomicrograph of Permian travertine showing carbonate crystals developed between layers of red silt (black), from red beds of Toroweap α at Fossil Mountain ($\times 21.5$)



a



b

- a.* "Fucoids" from Kaibab β , North Rim, Grand Canyon
b. Mold of worm tube, Kaibab β , North Rim, Grand Canyon

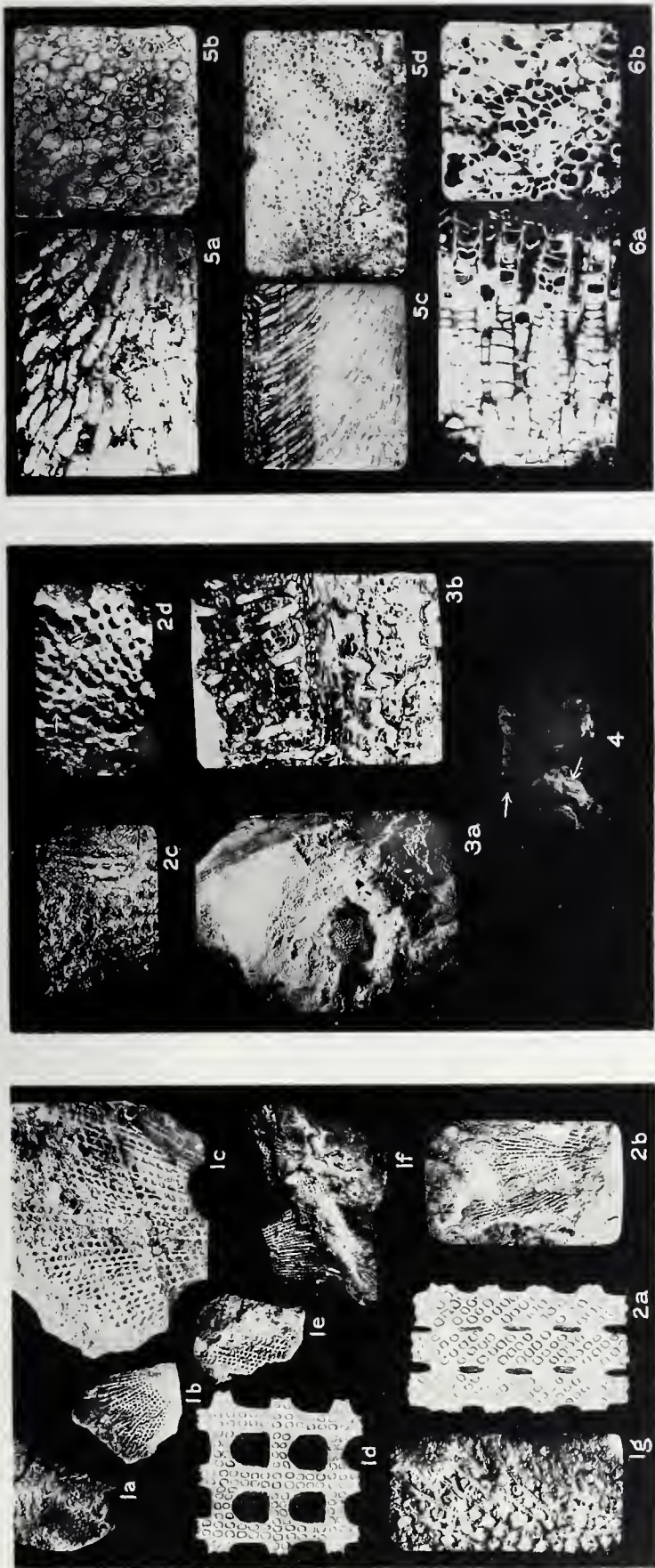


a



b

- a.* Trilobite trails, sandstone, base Kaibab α , Grand Canyon
b. Worm trails, sandstone, base Kaibab α , Grand Canyon



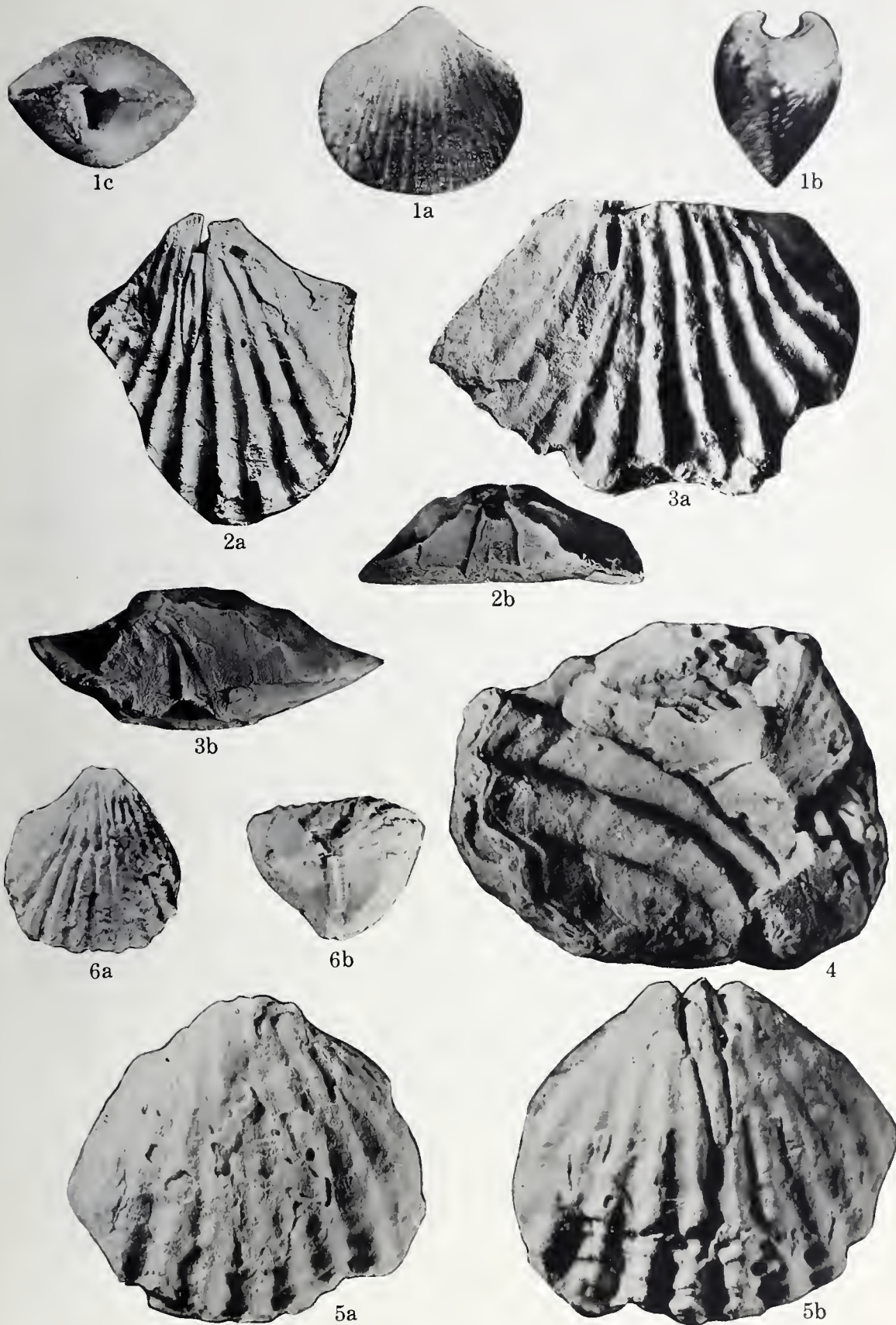
Bryozoa of Kaibab β , facies 1. (Photographs by David Keppel.) 1, *Septopora*. 2, *Poly-
pora*. 3, *Meekopora*. 4, *Rhombopora*. 5, *Stenopora*. 6, *Fistulipora*.



Pelecypods of Kaibab formation, facies 1 of β member

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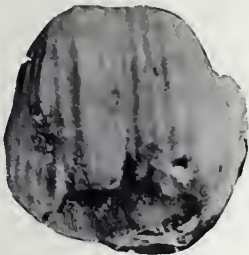
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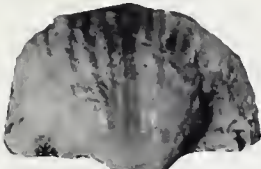


PLATE 46

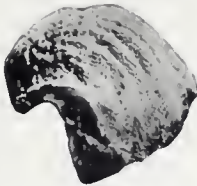
	PAGE
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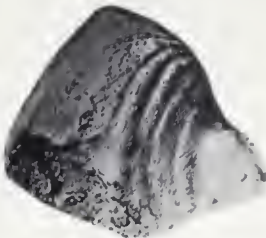
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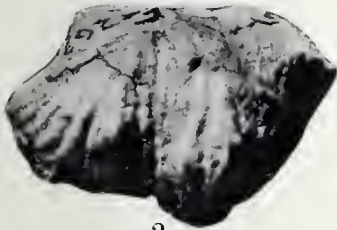
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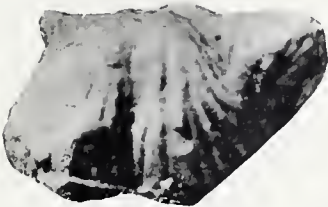
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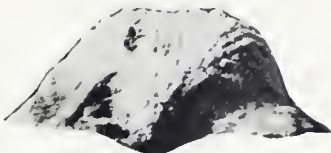
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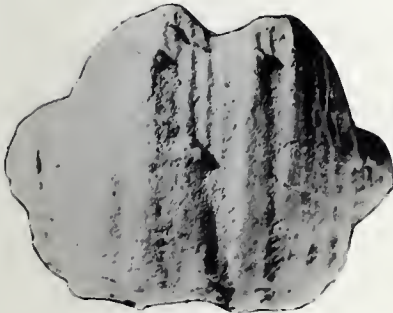
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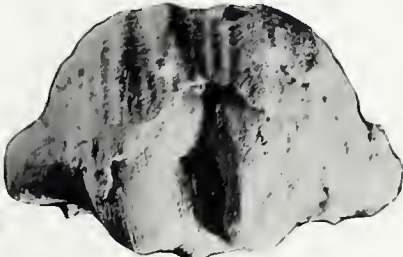
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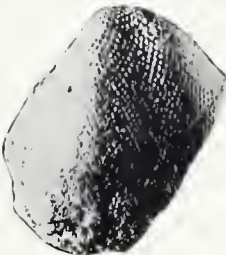
4c



5a



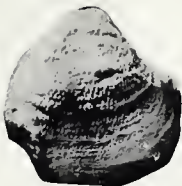
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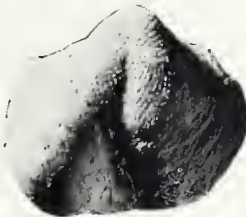
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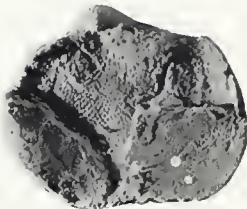
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8



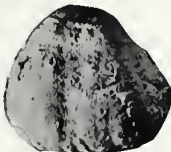
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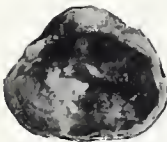
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9c



9a



9b



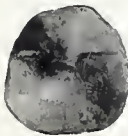
10



11c



11a



11b



11d

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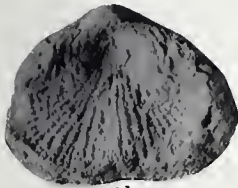
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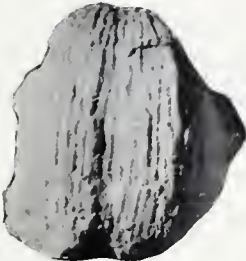
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3a



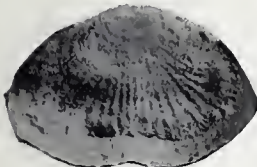
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4



3b



5



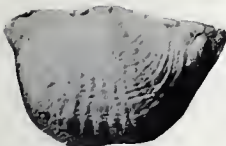
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6b



8



7



10b



10c



9



10a



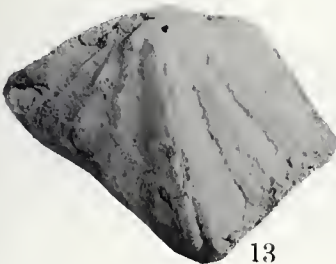
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11b



11a



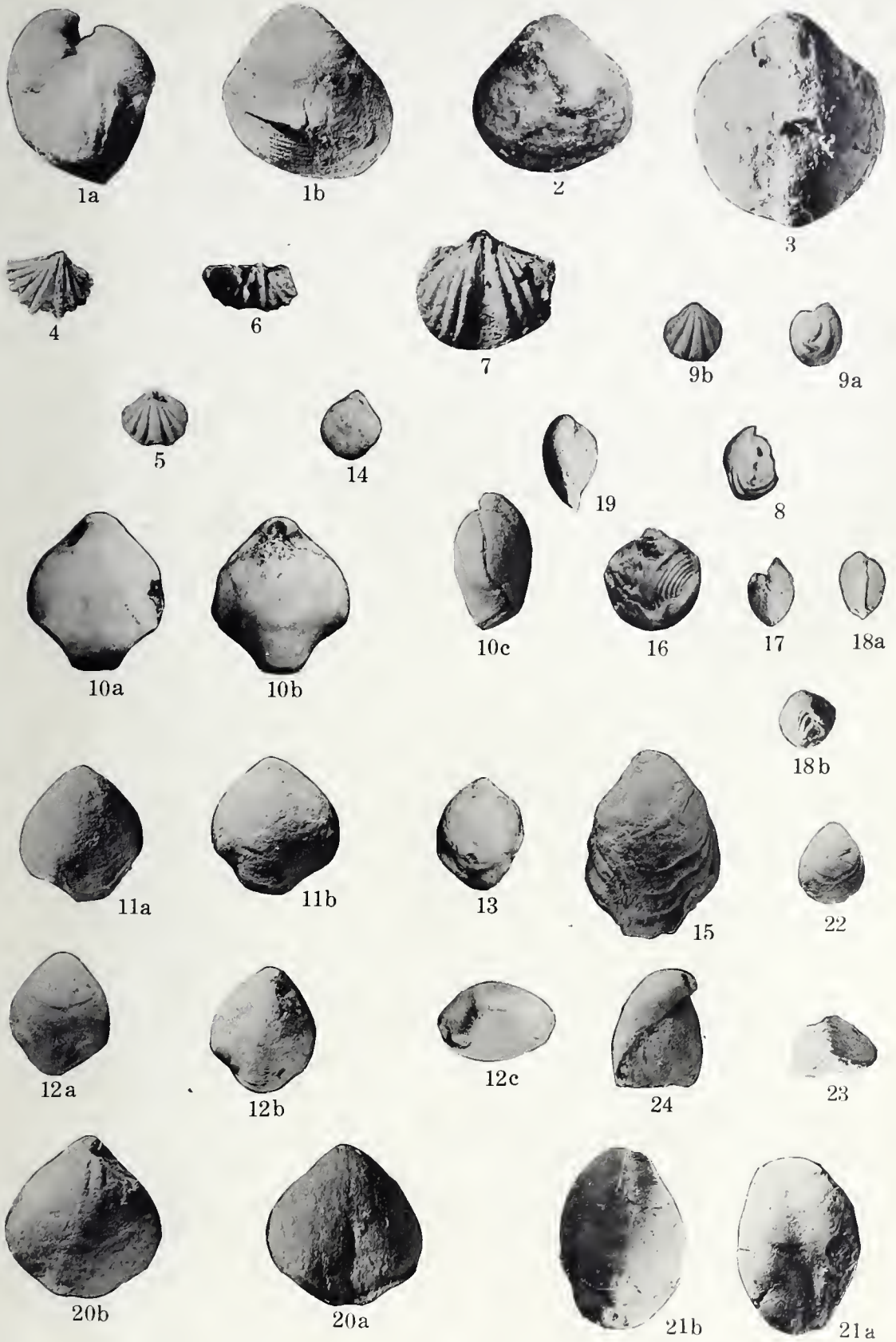
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